Interrelationships Among Large-Scale Atmospheric Circulation Regimes and Surface Temperature Anomalies in the North American Arctic

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By

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July 8, 2004

DEDICATION

Dedicated to my family and friends.

Thank you Mom, Dad and Elizabeth for encouraging me to embark on this adventure and stay focused these past two years. Simon, my thesis not only provided me with a great educational experience, but my best friend as well. Also thank you to everyone back home for complaining about the anomalously cold winter of 2002… it truly inspired me!

ACKNOWLEDGEMENT

It is with great gratitude that I thank first and foremost, my thesis advisor, Dr. Judith Curry, for her professional advice and financial support. I am truly honored to have had the opportunity to work with such a great scientist. The experiences and adventures I have gained from working with Dr. Curry are invaluable and unforgettable and I look forward to my future work with her. I would also like to thank Dr. Peter Webster and Dr. Robert Black for accepting to be in my thesis reading committee. I also need to express my deepest appreciation to Dr. Jiping Liu for the many hours he has sacrificed and his guidance and patience. Dr. Liu's help has been highly invaluable.

Without the help of Dr. Dana Hartley, Dr. Robert Black and Samuel Hunt I don't think I would be completing my master's degree here at Georgia Tech. I will never forget your kindness and the trust you put in me my first semester here.

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CHAPTER 1

INTRODUCTION

The impacts that large-scale atmospheric circulation regimes such as El Nino Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) have on the weather and climate systems of the Arctic are vital to understanding how and why surface air temperature changes in these northern regions. Generally the oscillations inherent in these large-scale atmospheric circulation regimes are well characterized, facilitating the interpretation of temperature change in the Arctic. Interpretation of the variations of surface temperature in the context of these regimes may help separate the contributions of internal variability versus anthropogenically-forced climate change.

The focus of this study is to examine the mechanisms involved in the interactions among large-scale atmospheric circulation patterns and how they are related to surface air temperature anomalies in the North American Arctic. Historical temperature data sets of Fairbanks, Alaska and Montreal, Quebec have been analyzed with respect to large-scale atmospheric circulation index data sets to investigate surface temperature anomalies in winter during the period 1960 to 2002.

In the past, many studies have been performed to analyze the effects that one or two atmospheric circulation regimes have on surface temperature. The NAO has been found to control much of the climate variability from the United States to Siberia and from the Arctic to the subtropical Atlantic, especially during boreal winter, (e.g. Hurrell et al., 2004). Buermann et al. [2003] associate the interannual variability of air temperature in the Northern Hemisphere to ENSO and the Arctic Oscillation (AO).

CHAPTER 2

DESCRIPTION OF LARGE-SCALE ATMOSPHERIC CIRCULATION REGIMES

Many of the large-scale regimes are related; AO and NAO are thought to be the same dynamical phenomenon, (Deser, 2000). Both ENSO and PDO (Pacific Decadal Oscillation) are positively correlated with the Pacific-North American (PNA) teleconnection (e.g., Rodinov et al., 2003). Furthermore it has been observed that the occurrence of a strong phase of a particular large-scale regime may actually be induced by the presence of another. An example of this is the canonical ENSO patterns over North America that are most likely to occur during the years when ENSO and PDO in phase (e.g. Gershunov et al., 1998). In other cases, however, it seems that certain regimes are independent of each other; the annual correlation of AO with Nino3 SST is -0.05, (e.g. Kalnay et al., 1996) and NAO with PDO and PNA is -0.03 and 0.01 respectively, (e.g. Kalnay et al., 1996).

This study aims to describe the dynamical characteristics of six large-scale atmospheric circulation regimes, how they are interrelated and how these relationships have affected winter surface air temperature in the North American Arctic spanning a 43-year period. In order to gain more insight into the issues presented in this paper, each of the six regimes are described briefly.

2.1 ARCTIC OSCILLATION

The Arctic Oscillation, (AO) is a large-scale atmospheric circulation phenomenon in which there is an observed atmospheric sea level pressure oscillation between the polar regions of the Arctic and the middle latitudes (about 45 degrees north) on time scales ranging from weeks to decades. Throughout most of the year, the AO extends throughout the troposphere; however, from January through March this oscillation reaches the stratosphere where it acts to modulate the intensity of the polar vortex, (Thompson and Wallace, 1998). In the troposphere, the AO acts to modulate the strength of the primary east-west jet streams.

Surface temperature variations in the Canadian Arctic have been related to the AO, (Hurrell, 1995; Thompson and Wallace, 1998).

In general, during the positive phase of the AO periods of below normal Arctic sea level pressure (SLP), increased north Atlantic surface westerlies and warmer and wetter conditions exist in northern Europe (Hodges, 2000). The positive phase of the AO often coincides with a strong polar vortex. During the negative phase of the AO, the polar vortex weakens, allowing for cold arctic air to plunge southward bringing subfreezing temperatures into North America and Europe.

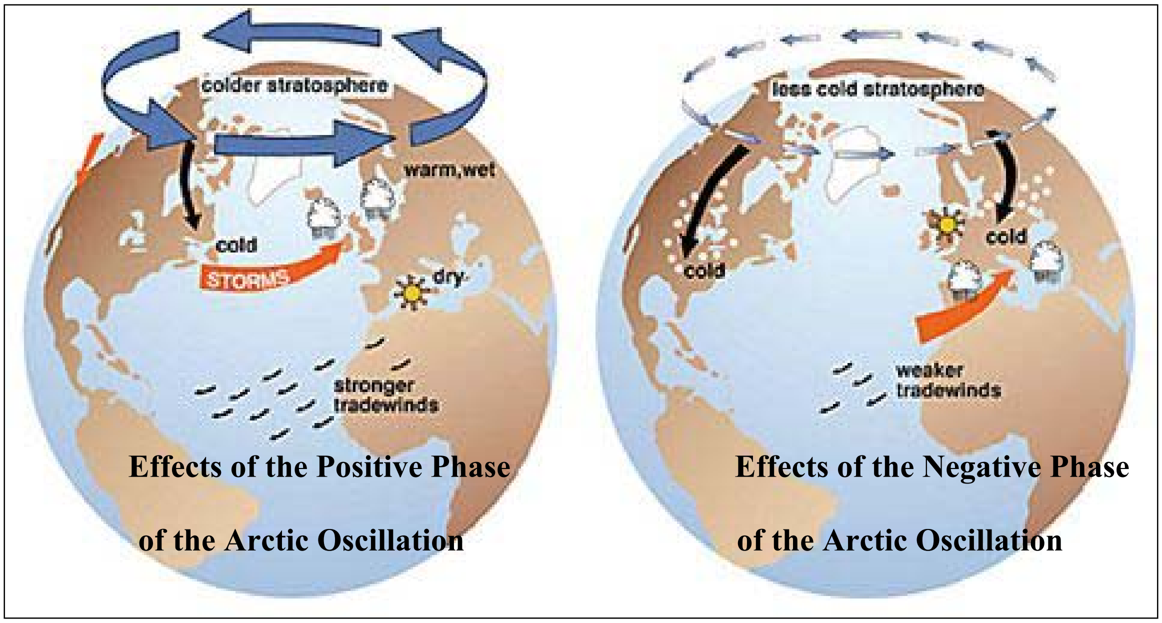

Figure 2.1 Effects of Arctic Oscillation (Thompson, D. W. J., and Wallace, J. M., 2000)

2.2 NORTH ATLANTIC OSCILLATION

The North Atlantic Oscillation, (NAO) is a north-south oscillation in atmospheric mass between the Icelandic Low and the Azores-Bermuda High, (e.g. Hurrell et. al, 2003). NAO influences climate variability from the eastern United States to Siberia and from the Arctic to the subtropical Atlantic. The amplitude of the NAO is most prominent during northern hemisphere winters, where it is responsible for over one-third of the total variance in SLP over the North Atlantic, (e.g., Hurrell et al., 2003).

Surface air temperature and sea surface temperature (SST) across wide regions of the North Atlantic Ocean, North America, the Arctic, Eurasia and the Mediterranean are significantly correlated with NAO variability, (e.g., Hurrell et al., 2003).

During the positive phase of the NAO, higher surface pressures south of 55°N are observed. Conversely, anomalously low pressure throughout the Arctic exists. This arrangement allows for increased westerlies over the mid-latitudes of the Atlantic, hence drawing moister and warmer air over most of Europe. A more southerly flow extends across eastern United States into southeast Canada.

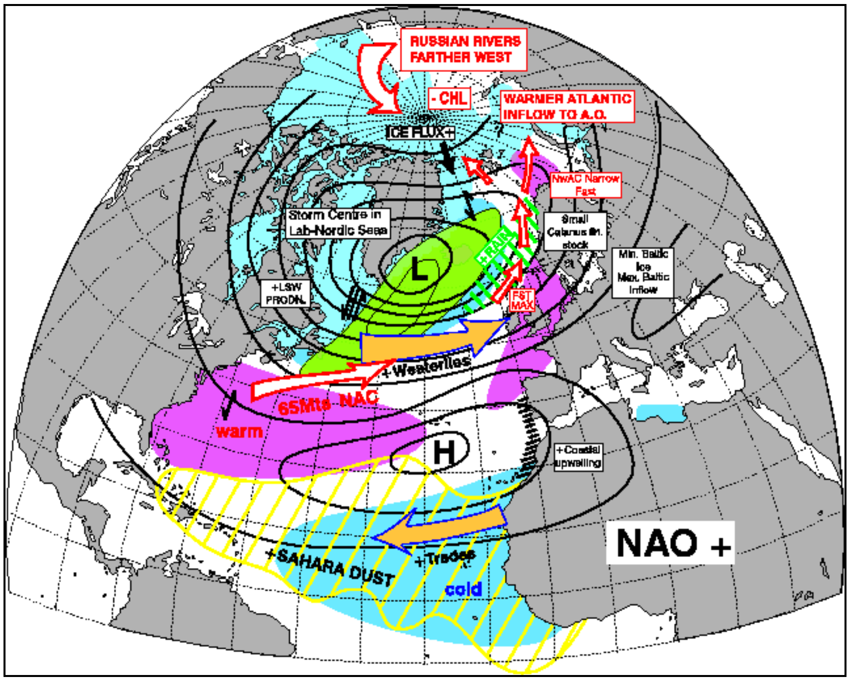

Figure 2.2 Positive Phase of NAO, (Stephenson, 1999)

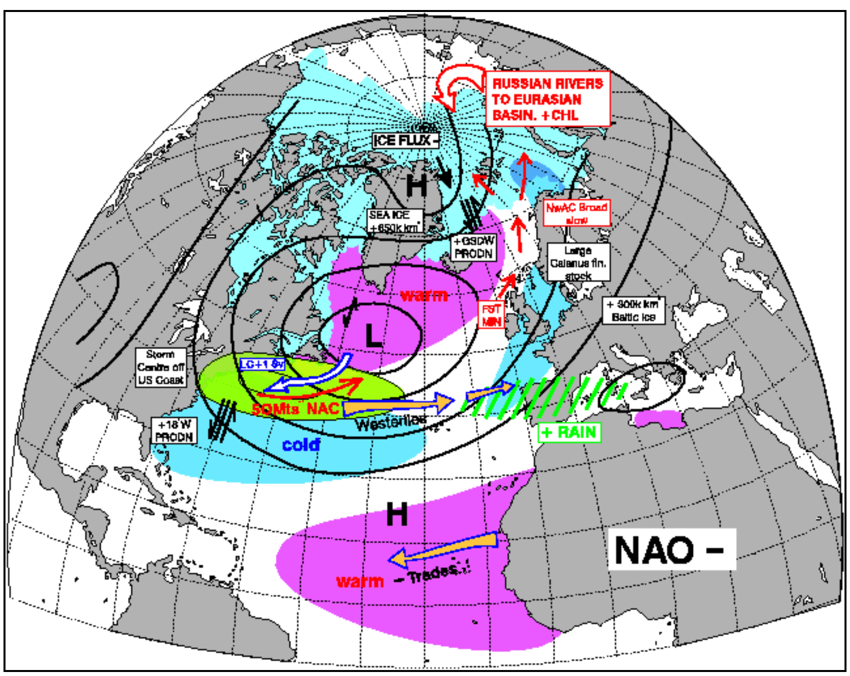

Figure 2.3 Negative Phase of NAO (Stephenson, 1999)

2.3 PACIFIC NORTH AMERICAN FLOW

The Pacific-North American, (PNA) flow can be described as alternating patterns of highs and lows extending from the southern portion of the Aleutian Islands to the west coast of North America and Southeast United States that has a tendency to be more well-defined in winter. The PNA is one of the most prominent modes of low-frequency variability in the Northern Hemisphere extratropics (Nigam, 2003).

The time series of the PNA shows variations on seasonal, interannual and interdecadal time scales. For example, from 1964-1967 a negative phase dominated, while a positive phase was observed from 1976-1988. Then during the 1989-1990 period a negative phase was seen again, followed by an extended positive phase from fall 1991to early spring of 1993.

During the positive phase of PNA, (Figure 2.4), a wave pattern can be seen across the North American continent. A large anomalous ridge across the North American continent allows for warmer temperatures and decreased storm frequency in the northwest, while drawing in cooler air into the southeast. Two troughs can be observed adjacent to the ridge, one in the Pacific and the other in southeast U.S.

A more zonal flow across the United States is a key feature of the negative phase of PNA. A decrease in temperature and an increase in precipitation in the Northwest and increased temperatures to the southeast are also apparent, (Sheridan, 2003). Figure 2.5 shows that during winter, the circulation anomalies centered over the Aleutians extends over most of the northern latitudes of the North Pacific.

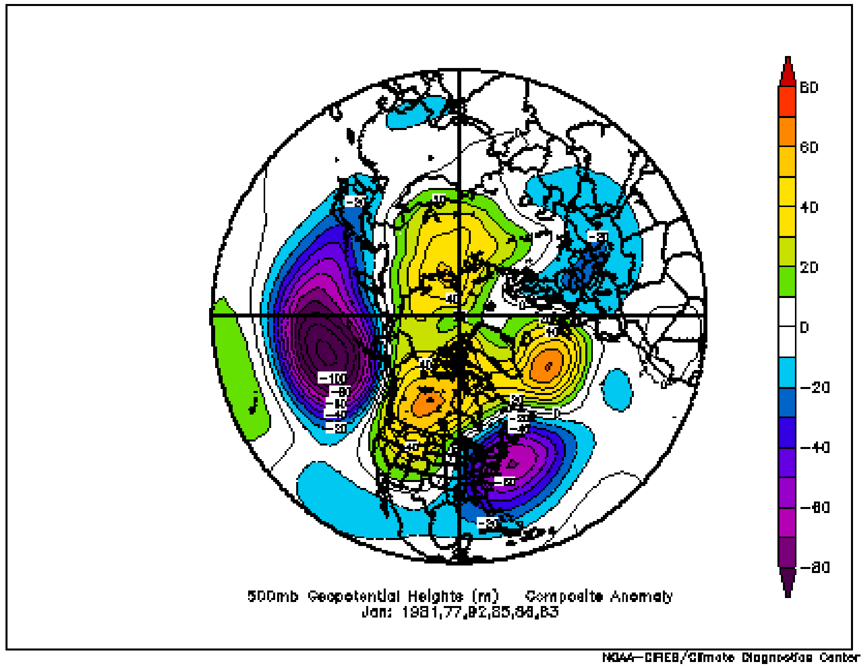

Figure 2.4 500mb Geopotential Heights (m) during Positive Phase of PNA
(Climate Diagnostics Center, 2001)

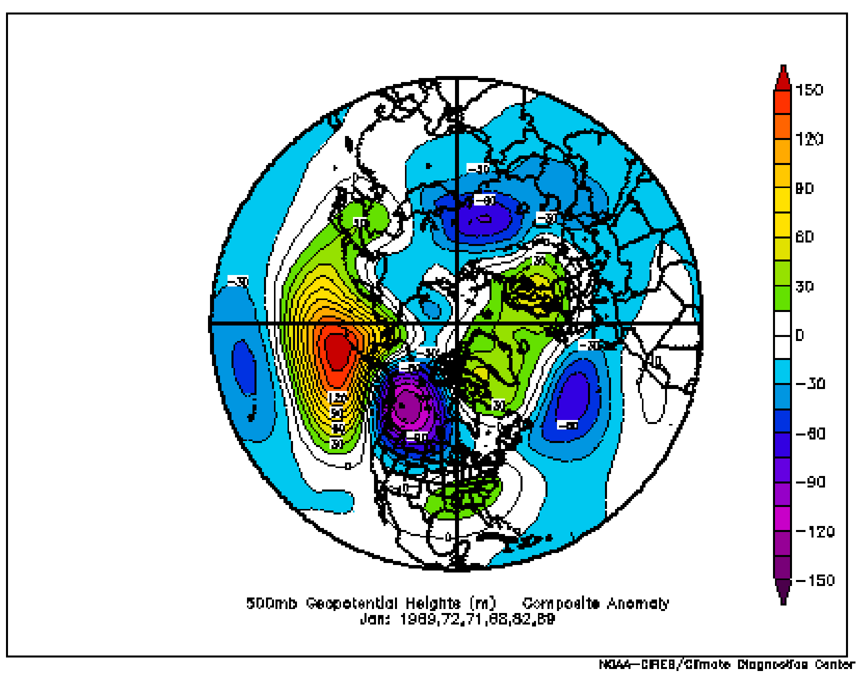

Figure 2.5 500mb Geopotential Heights (m) during Negative Phase of PNA
(Climate Diagnostics Center, 2001)

2.4 PACIFIC DECADAL OSCILLATION

While researching connections between Alaska salmon production cycles and Pacific climate, fisheries scientist Steven Hare coined the term “Pacific Decadal Oscillation” (PDO), (Mantua, 1999). PDO is defined as the leading principal component of North Pacific monthly sea surface temperature variability pole ward of 20N. PDO events can persist for 20 to 30 years and are most visible in the North Pacific/North American sector, (Mantua, 1999)

During a cold phase (negative PDO) colder water in eastern and tropical Pacific dominates with warmer water in the northwest Pacific and a weakened Aleutian low, (Mantua 2002). When in phase with a negative ENSO event, a cold PDO may also enhance La Nina events over North America.

Colder waters over the northwest North Pacific are present during the warm, (positive) phase of the PDO with warmer waters along the west coast of the Americas. The Aleutian low deepens. Winters in the south of the U.S. have been observed to be cooler and wetter while the north experiences drier and warmer winters.

Studies have shown that over the past century there have been two complete PDO cycles, (e.g., Mantua et al., 1997). The positive phase dominated from 1890-1924 and again from 1947-1976, while the negative phase prevailed from 1925-1946 and from 1977 through the mid-1990s, (e.g., Mantua et al., 1997).

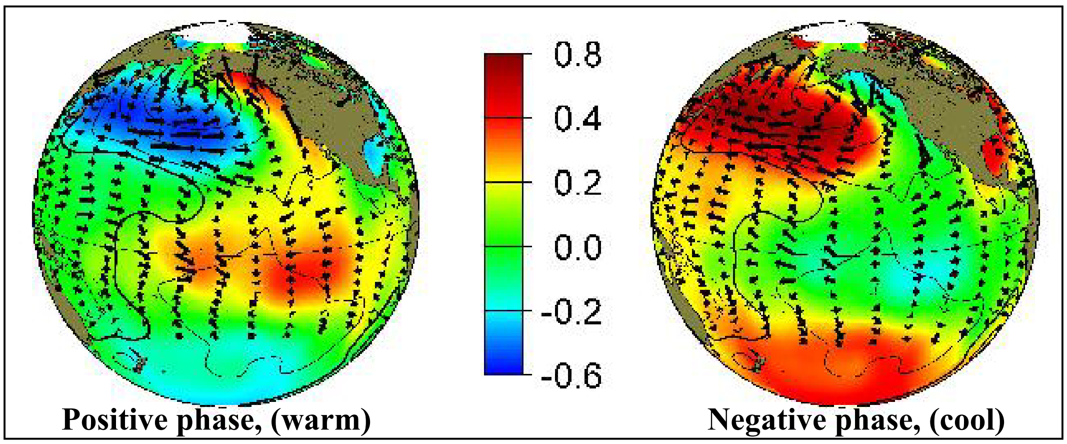

Figure 2.6 Positive and Negative Phases of PDO (Mantua, N.J., 2000)

2.5 NORTHERN OSCILLATION INDEX

The Northern Oscillation Index (NOI) is calculated by taking the difference in seal level pressure between the North Pacific and Darwin, Australia, (e.g., Schwing et al., 2002). The NOI can be considered as the north Pacific counterpart to the Southern Oscillation Index (SOI) that extends between the tropics and extratropics, (e.g., Schwing et al., 2002).

NOI alternates on decadal time scales, with an approximate 14-year cycle. Before 1965, during 1970 to 1976, from 1984 to 1991 and since 1998, NOI was primarily positive. Negative values were observed in 1965–1970, 1977–1983, and 1991–1998. Generally, a negative NOI is associated with weaker trade winds, less upwelling and an increase in SST in the Northeast Pacific. The opposite is true for the positive phase.

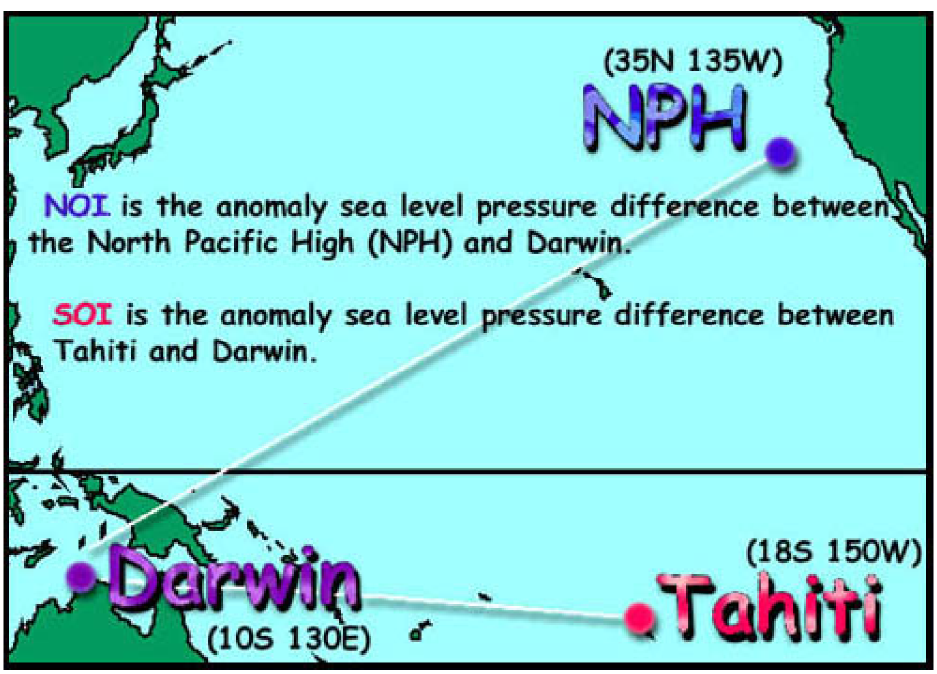

Figure 2.7 Definition of Northern Oscillation Index (Pacific Fisheries Environmental Laboratory, 2003a)

2.6 EL NINO SOUTHERN OSCILLATION

The El Nino Southern Oscillation (ENSO) is the main mode of interannual variability in the tropics. It represents an oscillation between atmospheric surface pressure at Darwin, Australia and Tahiti and induces a perturbation to the east-west Walker Circulation. If the SLP difference between Darwin and Tahiti is found to be negative, this coincides with an ocean warming, and is called El Nino, (for a summary see Nicholls, 2003). During an El Nino, the rising motion in the Walker cell is shifted east. Consequently, upper level westerlies decrease over the eastern tropical Pacific, leading to weakened subsidence at the west coast of South America. The resulting decrease in oceanic upwelling, as a result has unfavorable effects on fisheries off the coast of Peru. The weaker surface easterlies then complete the cycle.

In contrast, when the SLP difference between Darwin and Australia is positive, the ocean cools and is known as a La Nina event. During a La Nina event, coastal upwelling increases near in the eastern Pacific, cooling the region. La Nina and El Nino events are what make up the ENSO. Below are schematic diagrams that illustrate the changes in the Walker Circulation.

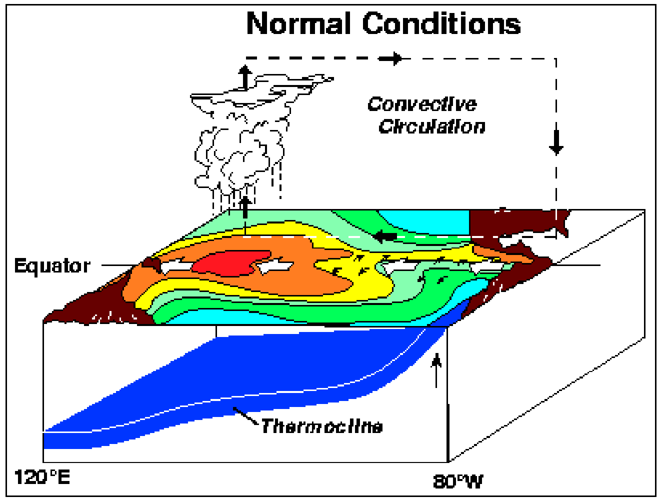

Figure 2.8 ENSO Neutral Conditions (NOAA, 2004a)

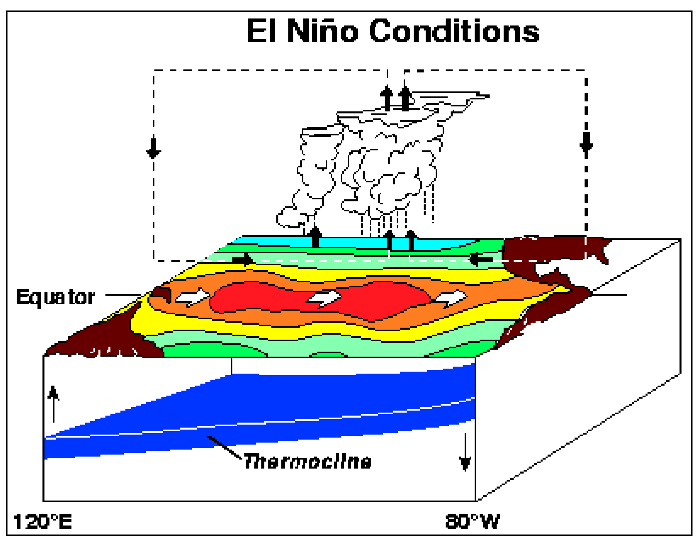

Figure 2.9 El Nino Conditions (NOAA, 2004a)

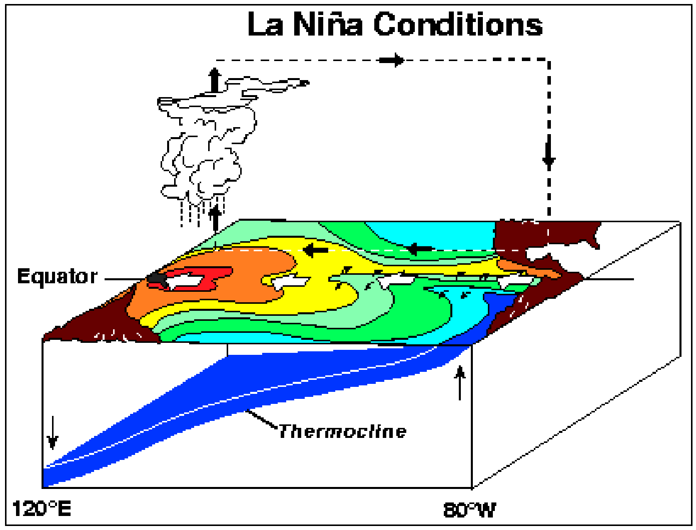

Figure 2.10 La Nina Conditions (NOAA, 2004a)

CHAPTER 3

DATA SETS

This study investigates the impacts that large-scale atmospheric phenomena have on temperature change in the North American Arctic during winter. The two cities selected for this study, Fairbanks, Alaska and Montreal, Quebec, represent western and eastern portions of the North American Arctic.

Monthly mean surface temperature data at Fairbanks and Montreal used in this study were obtained from The National Centers for Environmental Prediction (NCEP) re-analysis, (e.g., Kalnay et al. 1996) for the period from 1960 to 2002. Monthly mean sea level pressure (SLP) was also obtained from NCEP reanalysis over the same forty-three year period, (e.g., Kalnay et al. 1996). The data sets of the different large-scale atmospheric circulation indices were obtained from the Climate Diagnostic Center (CDC), at the Climate Indices website of Monthly Atmospheric and Ocean Time Series. Seasonal time series were computed by taking the mean of the time series from each season: spring, (March, April, May), summer, (June, July August), autumn, (September, October, November) and winter, (December, January, February).

The magnitude of the seasonal surface air temperature anomalies is greatest in winter. Fall does find strong temperature anomalies, but to a lesser extent, while the anomalies found in spring and summer are considerable smaller. At Fairbanks, winter surface temperature anomalies range from -8^{o}C to 7^{o}C and autumn surface temperature anomalies range from $-3\,^{o}$C to $6\,^{o}$C. In contrast, temperature anomalies range from $-3\,^{o}$C to $3\,^{o}$C in spring and $-2\,^{o}$C to $2\,^{o}$C in summer. In Montreal winter surface temperature anomalies range from $-3\,^{o}$C to $6\,^{o}$C and autumn surface air temperature anomalies range from -2 ^{o}C to 3 ^{o}C. In spring the anomalies range from –3 ^{o}C to 2 ^{o}C and in summer they range from –2 ^{o}C to 1.5 ^{o}C.

The majority of the large-scale atmospheric circulation indices show stronger signals in the winter and fall and to a lesser extent spring, coinciding with the seasons when the strongest temperature anomalies are observed. In summer the signals are weakest. An additional motivation for focusing on winter relationships between large-scale atmospheric circulation regimes and surface air temperatures arises from a phenomenon known as the spring-summer predictability barrier. In order to make seasonal forecasts, scientists examine climate patterns derived from global sea surface temperatures, with a particular focus on tropical Pacific SST (e.g. Gutzler, 2003). A large amount of the interannual variability of global large-scale atmospheric circulation regimes relates to fluctuations of Pacific SST (IPCC, 2001). Because the largest SST anomalies occur in boreal winter, interannual variability of the regimes is easier to explain. When spring arrives the signal of tropical Pacific SST weakens and the skill of forecasts drops, (McPhaden, 2003) not only for Nino 3 SST but also for other global large-scale atmospheric circulation regimes influenced by tropical Pacific SST. This is the spring-summer predictability barrier.

During the period considered here, a notable feature is the climate shift that occurred in the winter of 1976-77, (Karl, 1988; Wunsch, 1992), which is evident in the time series of monthly (DJF) temperature and various large-scale atmospheric regimes presented in Figures 3.1 to 3.8. At the time of the climate shift the climate system of the atmosphere and ocean abruptly shifted from its basic state, (Graham, 1994) with a noticeable deepening of the Aleutian low, (e.g., Miller et al. 1994). Ocean SSTs dropped in the central Pacific while a warming was observed off the west coast of North America, (e.g., Miller et al. 1994). Ebbesmeyer et al., [1991] described the 1976-1977 climate shift as step-like, with its effects fluctuating around this perturbed state for approximately 10 years afterwards, (Trenberth, 1990). Mantua et al., [1997] attribute the 1976-1977 climate shift to a shift in the PDO index from negative to positive index values.

Figures 3.1 to 3.4 are plots of monthly temperature anomalies for December, January and February temperature anomalies at Fairbanks and Montreal. The temperatures have not been normalized. Monthly averaged anomalous surface temperatures ranged from -15^{o}C to 10^{o}C. Many of these monthly anomalies are effectively smoothed once the seasonal averages were calculated. An example is in Montreal in 1989. A very large negative peak representing a monthly temperature anomaly of -8^{o}C can be observed in Figure 3.2. This anomaly occurred in December. January and February's temperature anomalies were 0.98^{o}C and 5.4^{o}C resulting in an insignificant seasonal average anomaly of -0.4^{o}C. Figures 3.5 to 3.8 demonstrate the December, January, February trends of Nino 3 SST and the PDO index before and after the climate shift. In Figure 3.1 it can be seen that surface air temperatures in Montreal before the climate shift show a slight positive trend. Following the climate shift, (Figure 3.2) a stronger positive trend is observed. Similarly, no trend is seen before the climate shift for winter values of Nino 3 SST (Figure 3.5), however following the shift a negative trend is observed (Figure 3.6). A similar pattern is observed in the PDO trends compared to the winter surface air temperatures trends at Fairbanks. Before the climate shift a slight cooling trend is observed (Figure 3.3) in conjunction with no discernable trend in PDO (Figure 3.7). After the shift the trends oppose each other with a tendency towards more positive surface air temperatures (Figure 3.4) and a stronger negative trend in PDO (Figure 3.8). It can be seen that Figures 3.7 and 3.8 are in agreement with Mantua et al. [1997]. The index values of PDO are predominantly negative prior to 1976 with an abrupt change to positive following 1976. The time scale coincides well with the 1976-1977 climate shift. The equation of each trend line is given on Figures 3.1 to 3.8.

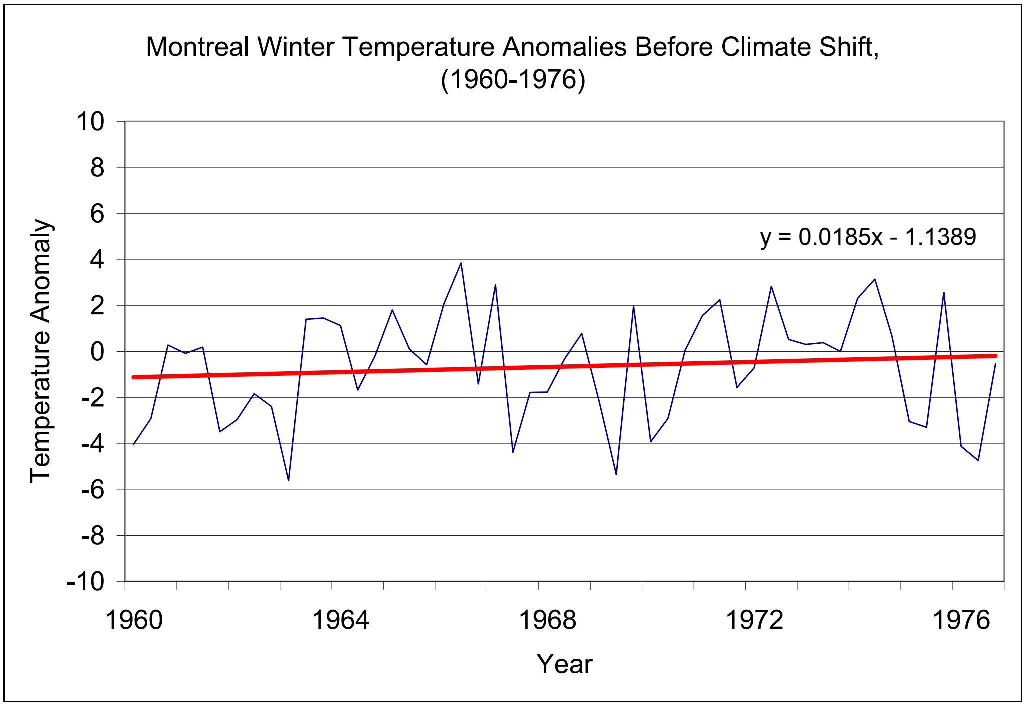

Figure 3.1 Montreal Un-normalized Winter Temperature Anomalies 1960-1976

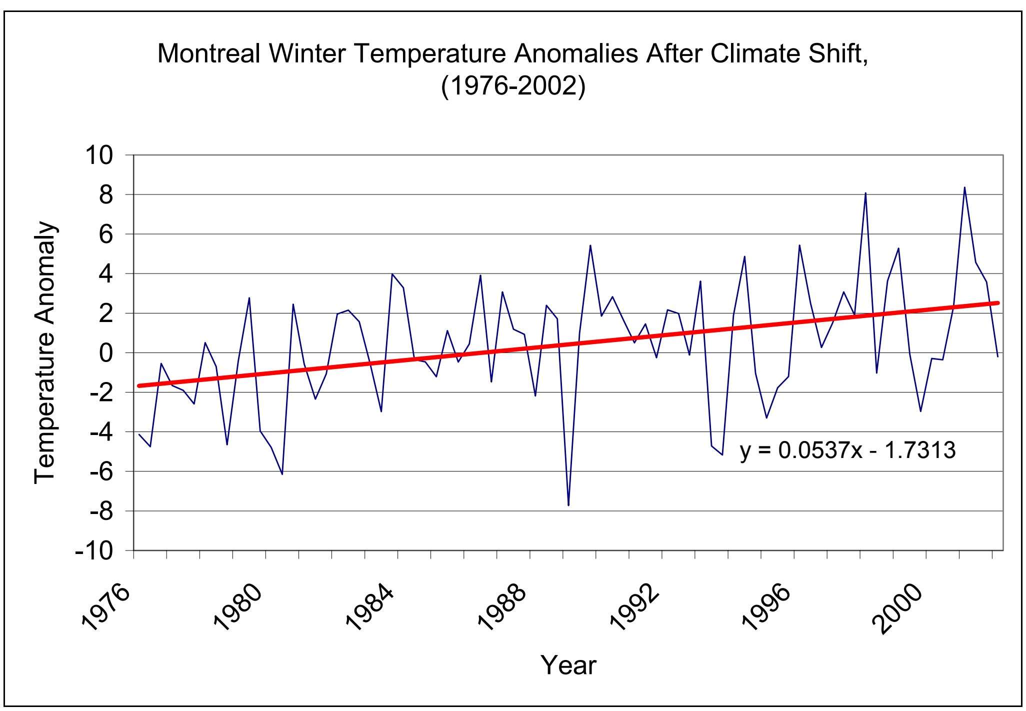

Figure 3.2 Montreal Un-normalized Winter Temperature Anomalies 1976-2002

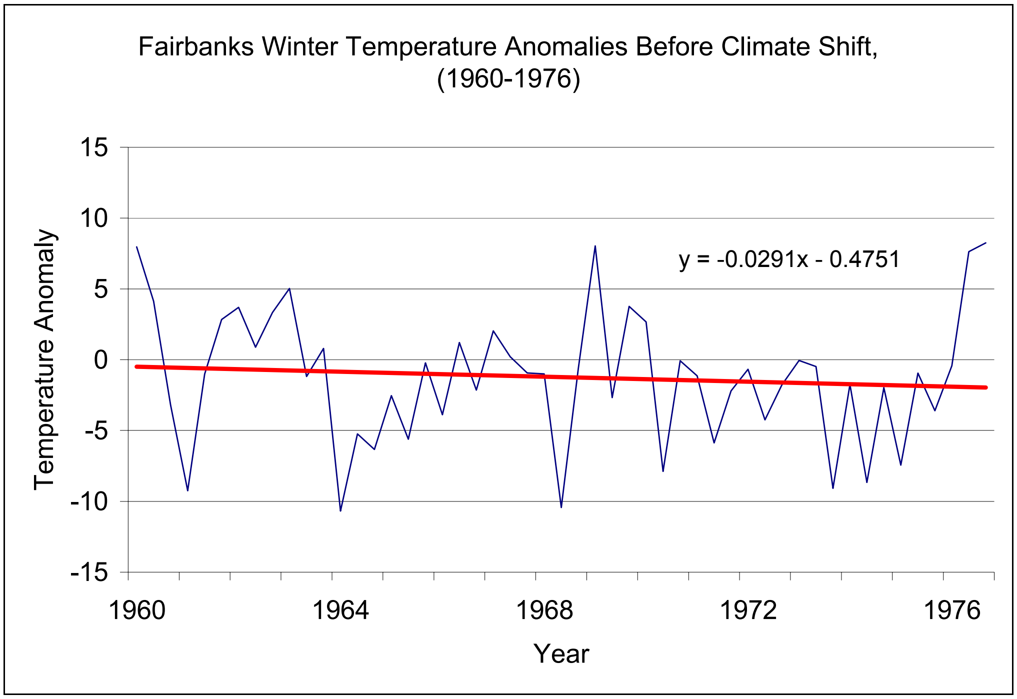

Figure 3.3 Fairbanks Un-normalized Winter Temperature Anomalies 1960-1976

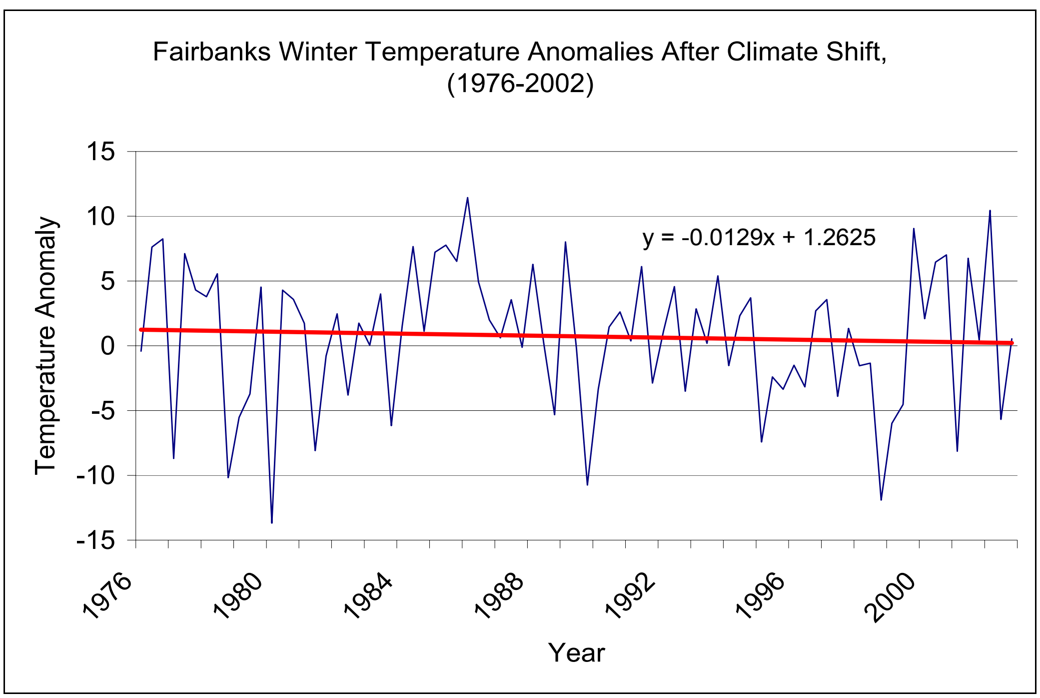

Figure 3.4 Fairbanks Un-normalized Winter Temperature Anomalies 1976-2002

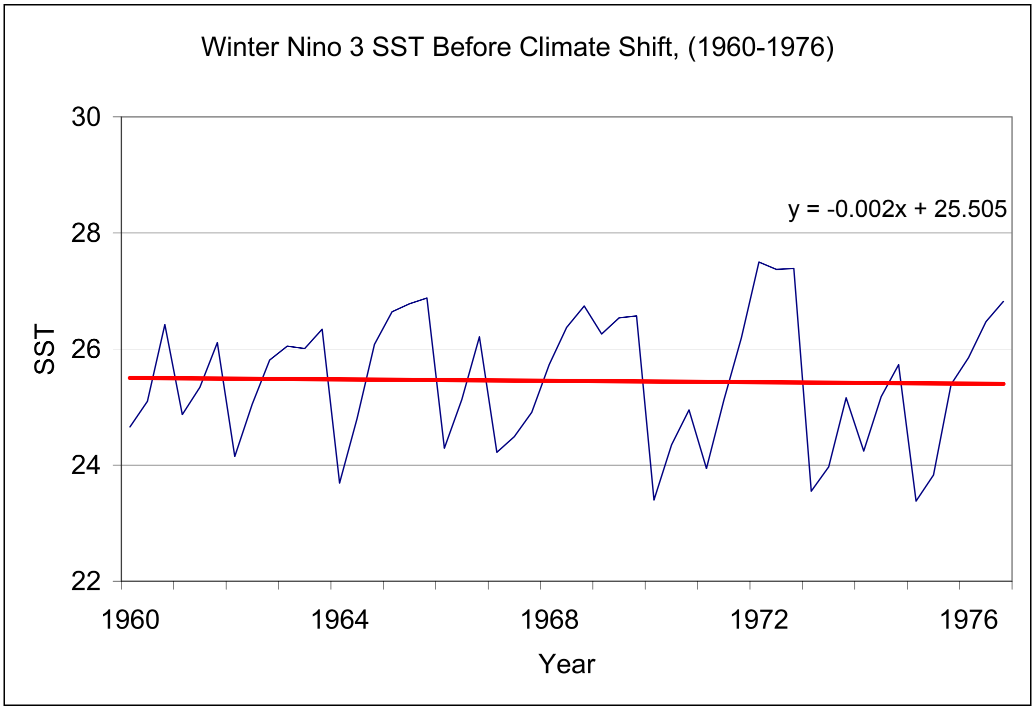

Figure 3.5 Winter Nino 3 SST Before Climate Shift

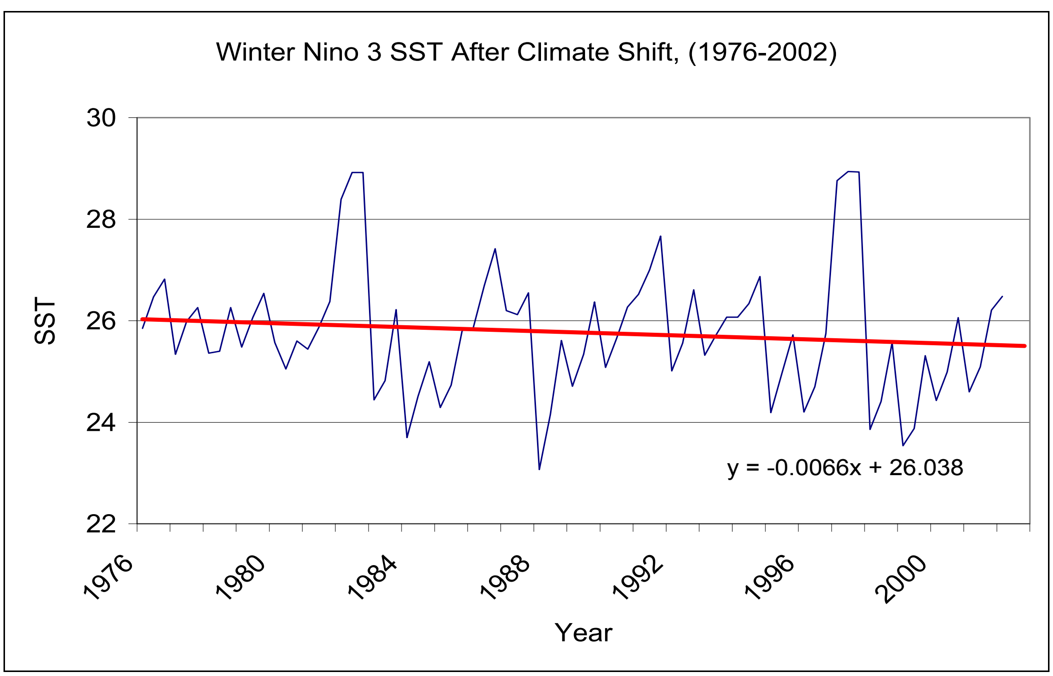

Figure 3.6 Winter Nino 3 SST After Climate Shift

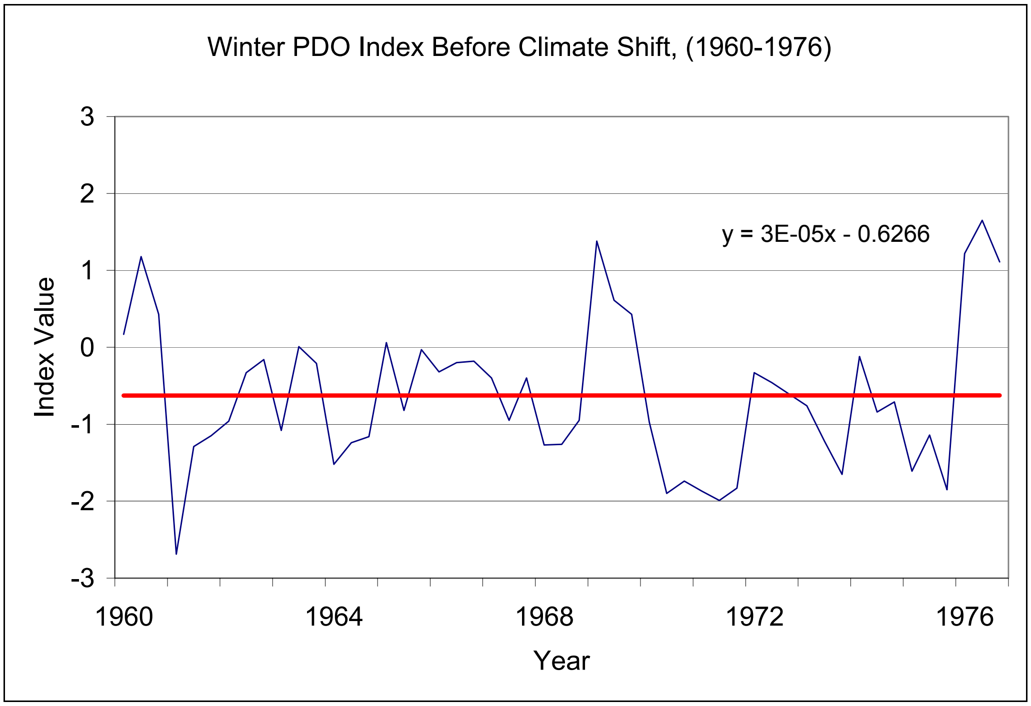

Figure 3.7 Winter PDO Index Before Climate Shift

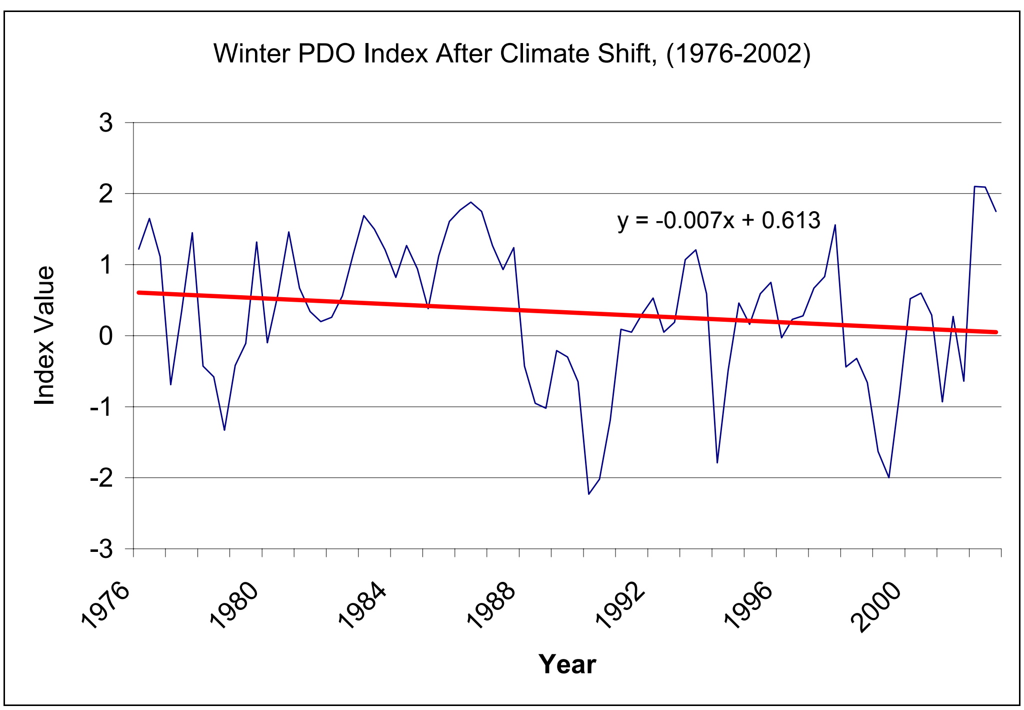

Figure 3.8 Winter PDO Index After Climate Shift

CHAPTER 4

LARGE-SCALE ATMOSPHERIC CIRCULATION REGIMES AND THEIR TELECONNECTIONS

Table 4.1 shows how the large-scale circulation indices correlate with one another during winter. The annual correlations given by Kalnay et al., [1996] between AO and Nino 3 SST of –0.05 and between NAO with PDO and PNA of –0.03 and 0.01 are lower than those seen in Tables 4.1 as Kalnay's include winter index values as well as fall, spring and summer values, seasons where overall, the correlation coefficients may be dampened. The correlation coefficient allows identification of the independence and interdependence of regimes and therefore provides insight as to how the regimes affect surface temperature.

To investigate the possibility that the climate shift may have altered the relationships between large-scale atmospheric circulation regimes after 1976, correlations of the large-scale indices with one another were computed separately for the period from 1960 to 1976 and from 1976 to 2002 for the winter (DJF) season. Correlations were performed by computing the seasonal averages of the time series and then performing correlations.

Table 4.1 Correlation of Large-scale Circulation Anomalies in Winter

60-02	El Nino	PNA	NAO	NOI	AO	PDO
El Nino	1	0.45	-0.16	-0.72	-0.14	0.43
PNA	0.45	1	0.03	-0.49	-0.20	0.63
NAO	-0.16	0.03	1	0.08	0.66	-0.07
NOI	-0.72	-0.49	0.08	1	0.17	-0.39
AO	-0.14	-0.20	0.66	0.17	1	-0.33
PDO	0.43	0.63	-0.07	-0.39	-0.33	1

60-76	El Nino	PNA	NAO	NOI	AO	PDO
El Nino	1	0.18	-0.13	-0.66	-0.26	0.50
PNA	0.18	1	-0.10	-0.04	-0.31	0.76
NAO	-0.13	-0.10	1	0.03	0.65	-0.15
NOI	-0.66	-0.04	0.03	1	0.39	-0.32
AO	-0.26	-0.31	0.65	0.39	1	-0.46
PDO	0.50	0.76	-0.15	-0.32	-0.46	1

76-02	El Nino	PNA	NAO	NOI	AO	PDO
El Nino	1	0.58	-0.30	-0.71	-0.17	0.37
PNA	0.58	1	-0.18	-0.59	-0.38	0.51
NAO	-0.30	-0.18	1	0.21	0.68	-0.37
NOI	-0.71	-0.59	0.21	1	0.14	-0.25
AO	-0.17	-0.38	0.68	0.14	1	-0.56
PDO	0.37	0.51	-0.37	-0.25	-0.56	1

Table 4.1 reveals numerous strong relationships between large-scale atmospheric circulation anomalies during wintertime. The correlation coefficient between Nino3 and PDO between 1960 and 2002 is 0.43. There are high correlations between AO and NAO (0.66) and between Nino3 and NOI (-0.72) during the same time frame as well. The winter season also finds a high correlation between PNA and PDO (0.63). While there are no considerable differences in these correlations before and after the climate shift, Table 4.1 does reveal that the 1976-1977 climate shift may have had an impact on the relationship between some indices.

A high correlation after the shift between NOI and PNA (-0.04 to -0.59) was observed. The PNA/Nino3 relationship was stronger after the climate shift, (0.18 to 0.58) as well.

The main relationships seen before the shift were between PNA/PDO and NOI/AO. Following the shift four additional high correlations can be seen; Nino3/PNA, PNA/NOI, NAO/PDO and AO/PDO.

The climate shift may not have been responsible for all the changes in relationships between large-scale atmospheric circulation regimes. Chapter 4 provides additional insight into how the climate shift may have altered the behavior of some large-scale atmospheric circulation regimes on seasonal time scales and how consequently surface air temperature may have been affected. Chapter 5 focuses on the relationships of other large-scale atmospheric circulation regimes since the climate shift, to winter surface air temperatures at Fairbanks and Montreal.

CHAPTER 5

LOCAL CORRELATION OF SURFACE TEMPERATURE ANOMALIES

Correlations between the large-scale indices and surface temperature anomalies are shown in Tables 5.1 to 5.4. Although high correlations may be observed in all seasons, for reasons presented in chapter 3, this study will focus on the winter season.

Table 5.1 Fairbanks: Correlations of Large-scale Indices with Spring, Summer and Autumn Temperatures

AO	Spring	Summer	Autumn	PNA	Spring	Summer	Autumn
1960 to 2002	-0.31	-0.16	-0.19	1960 to 2002	0.32	0.02	0.41
1960 to 1976	-0.2	-0.45	-0.23	1960 to 1976	0.12	0.1	0.55
1976 to 2002	-0.38	0	-0.29	1976 to 2002	0.48	-0.06	0.49
NAO				NOI			
1960 to 2002	-0.31	-0.03	-0.02	1960 to 2002	-0.11	-0.04	-0.38
1960 to 1976	-0.32	-0.11	-0.05	1960 to 1976	-0.21	-0.05	-0.35
1976 to 2002	-0.32	0.02	-0.03	1976 to 2002	-0.11	-0.08	-0.34
PDO				NINO			
1960 to 2002	-0.31	-0.09	0.36	1960 to 2002	0.18	0.1	0.48
1960 to 1976	0.65	0.16	0.7	1960 to 1976	0.25	0.28	0.59
1976 to 2002	0.18	-0.13	0.14	1976 to 2002	0.17	0.02	0.28

Table 5.2 Montreal: Correlation of Large-scale Indices with Spring, Summer and Autumn Temperatures

AO	Spring	Summer	Autumn	PNA	Spring	Summer	Autumn
1960 to 2002	0.02	0.12	0.10	1960 to 2002	-0.11	-0.07	-0.46
1960 to 1976	-0.21	0.36	0.35	1960 to 1976	0.03	-0.48	-0.63
1976 to 2002	0.13	0.13	-0.03	1976 to 2002	-0.08	-0.19	-0.42
NAO				NOI			
1960 to 2002	-0.14	0.08	-0.20	1960 to 2002	0.21	0.31	0
1960 to 1976	-0.41	-0.2	-0.17	1960 to 1976	0.42	0.44	0.33
1976 to 2002	0.04	0.22	-0.18	1976 to 2002	0.04	0.16	-0.14
PDO				NINO			
1960 to 2002	-0.11	-0.3	-0.36	1960 to 2002	0.03	-0.22	-0.21
1960 to 1976	0.21	-0.19	-0.61	1960 to 1976	-0.43	-0.48	-0.51
1976 to 2002	-0.01	-0.17	-0.56	1976 to 2002	0.23	-0.07	-0.27

Table 5.3 Fairbanks: Correlations of Large-scale Indices with Winter Temperatures

AO			PNA	
1960 to 2002	-0.29		1960 to 2002	0.57
1960 to 1976	-0.29		1960 to 1976	0.82
1976 to 2002	-0.43		1976 to 2002	0.41
NAO			NOI	
1960 to 2002	-0.34		1960 to 2002	-0.21
1960 to 1976	-0.22		1960 to 1976	-0.13
1976 to 2002	-0.13		1976 to 2002	-0.21
PDO			NINO	
1960 to 2002	0.60		1960 to 2002	0.24
1960 to 1976	0.77		1960 to 1976	0.27
1976 to 2002	0.43		1976 to 2002	0.15

Table 5.4 Montreal: Correlations of Large-scale Indices with Winter Temperatures

AO			PNA	
1960 to 2002	0.42		1960 to 2002	-0.15
1960 to 1976	0.39		1960 to 1976	-0.43
1976 to 2002	0.44		1976 to 2002	-0.23
NAO			NOI	
1960 to 2002	0.43		1960 to 2002	0.03
1960 to 1976	0.44		1960 to 1976	0.13
1976 to 2002	0.40		1976 to 2002	0.00
PDO			NINO	
1960 to 2002	-0.14		1960 to 2002	0.32
1960 to 1976	-0.34		1960 to 1976	0.75
1976 to 2002	-0.35		1976 to 2002	0.01

The following paragraph points out some of the more noteworthy relationships found in Tables 5.3 and 5.4. Nino 3, AO and NAO have a stronger correlation to winter temperatures in Montreal as opposed to winter temperatures in Fairbanks. NOI, PDO and PNA have stronger correlations to winter temperatures in Fairbanks as opposed to winter temperatures in Montreal. The correlations of AO, NAO and NOI to winter temperatures at Montreal and Fairbanks remains approximately constant before and after the climate shift.

Many of the correlation coefficients, (in all seasons) between temperature and the indices drop considerably following the climate shift. Examining the correlation coefficients of Nino 3 to winter surface temperatures in Montreal and the correlation coefficients of the PDO and PNA index values to winter surface temperatures in Fairbanks reveals a definite impact from the climate shift. Prior to the climate shift Nino

3 SST correlated highly with Montreal winter temperatures (0.75). Following the shift, the correlation coefficient dropped to 0.01. Similarly, PDO and PNA correlations with winter temperatures in Fairbanks were 0.82 and 0.77 before the climate shift dropping to 0.41 and 0.43 following the shift. Comparing Figures 3.1 and 3.2 and Figures 3.3 and 3.4 with Figures 3.5 and 3.6 and Figures 3.7 and 3.8 demonstrates this point. The stronger contrast of opposing trends of Montreal winter temperatures and Nino 3 SST following the shift explains the drop in correlation coefficient observed in Table 5.4, which indicates that the time series should correlate positively. A similar pattern is observed in the PDO trends compared to the winter surface air temperatures trends at Fairbanks. Before the climate shift a slight cooling temperature trend is observed (Figure 3.3) in conjunction with no trend in PDO (Figure 3.7), re-enforcing the positive correlation value of 0.7 presented in Table 5.3. After the shift the trends oppose each other with a positive surface air temperature trend (Figure 3.4) and a negative trend in PDO (Figure 3.8). The opposing trends following the climate shift therefore explain the drop in correlation coefficient after 1976 to a value of 0.14. The appearance of a shift in Nino 3 SST and PDO are consistent with the findings of Miller et al. [1994] who recognized the changes in Pacific SST and a deepening of the Aleutian Low following the climate shift.

CHAPTER 6

INTERPRETATION OF SURFACE TEMPERATURE ANOMALIES

In this chapter, we examine the superposition of the different regimes in determining winter surface temperature anomalies in Fairbanks and Montreal following the climate shift, from 1977 to 2002.

For a period of twenty-six years, winter surface air temperature time series and the large-scale atmospheric circulation indices were normalized by: $Z = \frac{X - \mu}{\sigma}$ where X is the value to be normalized, (e.g., temperature of a chosen year), μ is the mean and σ is the standard deviation of the time series. Anomalous temperature events are defined as temperatures anomalies that exceed one standard deviation from the mean.

6.1 FAIRBANKS

6.1.1 OBSERVATIONS

Between 1977 and 2002, there were four years at Fairbanks that experienced positive surface air temperature anomalies during winter and two years that experienced negative surface air temperature anomalies. Table 6.1 presents the winter temperature anomalies for each year, as well as the normalized values of the large-scale atmospheric circulation indices that occurred in the same years. The last column represents volcanic activity and is denoted by an “X” if a significant volcanic eruption occurred that year. The years are color-coded to indicate whether a negative, positive or neutral surface air temperature anomaly was observed in the given year. Overall, positive PDO and PNA indices and negative AO indices are associated with positive winter temperature anomalies in Fairbanks. Positive NOI indices and to some extent La Nina events are the primary indices associated with negative winter temperature anomalies. This is in agreement with Table 5.3 that indicates that PDO and PNA correlate positively and NOI and AO correlate negatively with winter temperatures at Fairbanks. Discrepancies are noted when comparing Table 6.1 to Table 5.3. In 1984, (a positive temperature anomaly) ENSO is negative and in 1985, (a negative temperature anomaly) AO and NAO are negative. ENSO should correlate positively and AO and NAO should correlate negatively with winter surface air temperatures at Fairbanks. This will be further explored.

Table 6.1 Fairbanks Winter Temperature Anomalies and Associated Anomalous Indices

Year	T Anomaly	Ao Anomaly	Nao Anomaly	Noi Anomaly	Nino 3 Anomaly	Pdo Anomaly	Pna Anomaly	Volcano
1977	0.34	-1.20	-1.15	-1.86	0.21	0.37	1.05	
1978	-0.04	-1.30	-2.16	-0.02	0.03	-0.78	-1.64	
1979	-0.46	-0.57	-0.54	-1.59	0.36	0.26	0.19	
1980	-0.57	-0.17	0.30	-0.57	-0.22	0.65	1.38	
1981	-0.72	-0.38	-1.00	0.06	0.24	0.40	-1.16	
1982	0.09	0.17	0.97	-2.21	2.87	0.65	1.58	**X**
1983	-0.18	0.26	0.99	0.40	-0.44	1.47	0.27	
1984	1.15	-1.27	-0.60	0.70	-1.09	1.01	-0.95	
1985	2.35	-1.81	-0.95	-0.74	-0.65	1.04	1.58	
1986	2.02	-0.85	-0.49	-0.36	0.94	1.80	0.97	
1987	0.48	-0.45	-0.39	0.31	0.60	1.15	0.28	
1988	0.17	2.69	1.70	1.63	-1.26	-0.80	-1.40	
1989	-0.27	1.25	0.55	0.52	-0.15	-0.39	-1.04	
1990	0.12	0.37	0.72	0.47	0.02	-1.81	-0.78	
1991	0.43	1.10	1.17	-1.45	1.32	0.15	0.53	**X**
1992	0.28	1.77	1.23	-1.30	0.08	0.26	-0.68	
1993	0.95	-0.42	0.16	0.18	0.06	0.96	-0.48	
1994	0.53	0.72	0.70	-1.51	0.73	-0.61	0.68	
1995	-1.36	-1.05	-1.04	-0.30	-0.63	0.50	0.05	
1996	-0.16	-0.10	-0.13	0.28	-0.70	0.16	0.07	
1997	0.16	-0.78	-0.36	-1.90	3.00	1.02	1.03	
1998	-1.54	0.65	0.35	1.57	-0.95	-0.47	-0.56	
1999	-0.11	1.13	0.84	0.37	-1.29	-1.49	-0.32	
2000	1.72	-1.31	-0.69	0.60	-0.44	0.47	0.50	
2001	-0.05	0.45	-0.34	0.57	-0.31	-0.43	-0.46	
2002	0.62	-0.65	-0.70	-0.70	0.81	1.98	0.71	

	Positive Anomaly
	Negative Anomaly

6.1.2 ANALYSIS

In this section, we consider specific years that appear to reflect complex interactions among the different indices.

Fairbanks experienced anomalously warm winter temperatures in 1984, 1985, 1986 coinciding with positive PDO index values. In 1984 this was compounded by a negative AO index and in 1985 both a negative AO index and a positive PNA index was observed. In 1984 a La Nina event was also observed, but was overpowered by the positive PDO and negative AO indices. When PDO is in its positive phase the Aleutian low deepens, (Mantua, 2002). This deepening causes an increase in cyclonic circulation that advects warmer air from the south or southeast flank of the low into Alaska.

The effect that a positive PNA index has on surface air temperature at Fairbanks is similar to that that of a positive PDO index. Rodionov et al., [2003] stated that during warm PDO phases atmospheric circulation resembles the classical PNA pattern. In the positive phase of PNA a meridional wave-like pattern is established across the United States, with a low-pressure system positioned in the Pacific off the west coast of North America, followed by a high extending from the western portion of North America to central North America, followed by a low pressure system in the east. The low in the Pacific seen in the positive phase of PNA perpetuates similar responses as the deepening of the Aleutian low seen during a positive PDO index. Thus, the strong positive PNA index observed in 1985 in combination with the strong positive PDO index acted to induce warm temperature anomalies at Fairbanks.

The positive temperature anomalies at Fairbanks in 1984 and 1985 partially induced by the positive PDO and PNA indices were compounded by negative AO indices in these same two years, (-1.27, -1.81). Associated with negative AO episodes is a weak, more disorganized polar vortex, (Baldwin and Dunkerton, 2001). The polar vortex is essentially the polar branch of the jet stream circling the northern hemisphere. While the highly irregular, undulating jet stream characteristic of a negative AO index places much of North America in a deep trough of cold air; a ridge of high pressure can form over Alaska causing low level warm advection to the west of this high leaving the state with anomalously warmer temperatures. Figure 6.1 depicts the geopotential height field at 500mb during a negative AO index. The greatly distorted jet stream places a large high-pressure system over the west, including Alaska. A negative AO index, (-1.31) in 2000 may have also contributed to anomalously warm temperatures in Fairbanks.

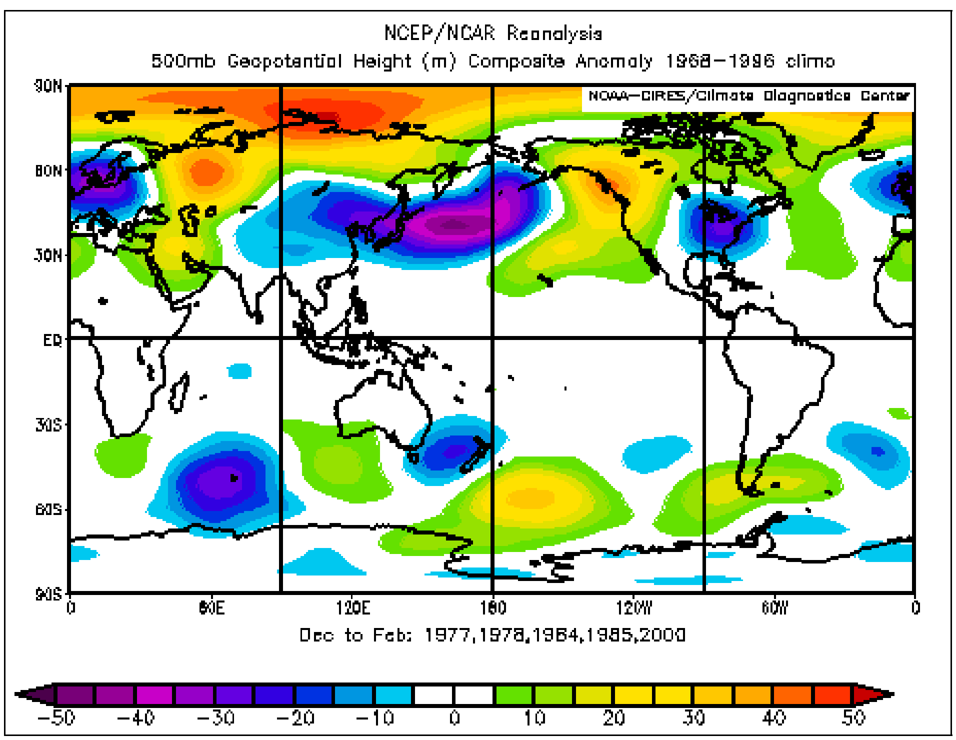

Figure 6.1 Geopotential Height Field at 500mb during a Negative AO Index
(e.g., Kalnay et al., 1996)

Fairbanks experienced anomalously cool winter temperatures in 1995 and 1998. In 1995 negative AO and NAO indices were observed (-1.05 and –1.04), but it was likely that the weak La Nina, (-0.63) observed that same year had a greater affect on inducing a negative temperature anomaly. During a La Nina the surface pressure off of Peru increases, leading to cooler waters in the tropical east Pacific, [NOAA, 2004b]. Similar to El Nino, although opposite, a series of meridional interactions ensues. This causes the surface low-pressure systems around the Gulf of Alaska to be weaker than normal, favoring the build-up of colder than normal air over Alaska, (Rozell, 1999).

In 1998 a strong positive NOI index, (1.57) may have been associated with a negative temperature anomaly at Fairbanks. The surface trade winds in the Northern Hemisphere generally move from the northeast to southwest, beginning in the vicinity of the North Pacific High and extending towards Darwin, Australia, (e.g., Schwing et al. 2002). When the NOI index is positive, the trade winds grow stronger, transporting cooler air equatorward, leading to more upwelling and a decrease in SST in the Northeast Pacific, (e.g., Schwing et al. 2002). Similarly, increasing the trade winds at the surface transports air away from the high-pressure system. To compensate, there is an increase in subsidence that acts to intensify the surface pressure, thereby further increasing the anticyclonic circulation. The diagram below demonstrates the circulation pattern associated with NOI and its southern hemisphere counterpart, SOI.

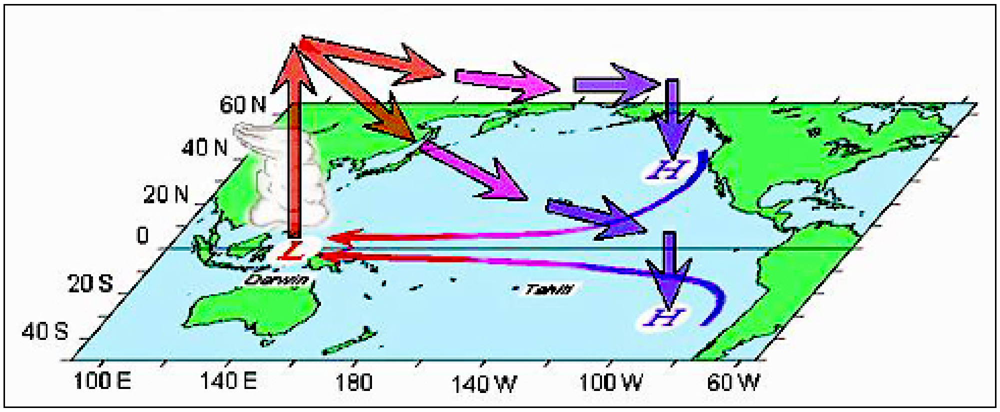

Figure 6.2 Northern Oscillation Index Circulation Cell
(Pacific Fisheries Environmental Laboratory, 2003b)

6.1.3 INSIGNIFICANT TEMPERATURE ANOMALIES

There were many years in which large-scale atmospheric circulation regimes were anomalously strong however no anomalous winter temperatures at Fairbanks resulted. The most prevalent reason for the insignificant temperature anomalies with concurrent anomalous large-scale atmospheric circulation regimes at Fairbanks are dampening effects among competing large-scale circulation regimes. For example, the sign of one large-scale regime may act to cool a region. If another large-scale regime that acts to warm the same region occurs simultaneously then the region may cool or warm, but insignificantly due to canceling effects.

Volcanic eruptions may be an additional influence on surface temperature anomalies, acting to cool the surface. In 1982 Mount Chichon in Mexico erupted. The strong El Nino of 1982-1983 probably would have induced significant warming, but the cooling effects of the El Chichon's eruption may have caused the weaker positive temperature anomaly, (e.g., Mao et al., 1998). The effects of this eruption ran into 1983 causing cooler than normal temperatures. This eruption negated the warming effects that otherwise may have been associated with a concurrent positive PDO. Stenchikov et al. [2004] showed that the 1991 eruption of Mount Pinatubo in the Philippines was associated with anomalies in the Northern Hemisphere extratropical winter circulation that led to positive phases of the Arctic Oscillation during the two boreal winters following the eruption. The positive AO response may have dampened any warming effects that the simultaneous positive ENSO event may have caused.

6.2 MONTREAL

6.2.1 OBSERVATIONS

Eleven of the 26 years following the climate shift examined in this study had winter surface air temperature anomalies at Montreal. Of the eleven years, five were anomalously cool and six were anomalously warm. In 1993 a cold surface air temperature anomaly occurred and in 2001 a warm surface air temperature anomaly occurred. There were no large-scale atmospheric circulation regimes exceeding one standard deviation in either of these two years. There are some key patterns that can be observed in Table 6.2. All the large-scale regimes examined in this study have occurred in association with winter temperature anomalies at Montreal since 1977, generally consistent with the higher correlation coefficients presented in Table 5.4. The correlation coefficients of NOI and Nino 3 with winter temperatures at Montreal falls considerably after the climate shift. While NOI probably plays a secondary role, strong ENSO events that go against the trend found in Figure 3.6 may induce winter temperature anomalies at Montreal.

Generally AO/NAO and Nino3, positively correlate with Montreal winter temperatures. This is confirmed in Table 5.4. PDO and PNA correlate negatively with winter temperatures in Montreal.

Table 6.2 Montreal Winter Temperature Anomalies and Associated Anomalous Indices

	T Anomaly	Ao Anomaly	Nao Anomaly	Noi Anomaly	Nino 3 Anomaly	Pdo Anomaly	Pna Anomaly	Volcano
Year								
1977	-1.11	-1.20	-1.15	-1.86	0.21	0.37	1.05	
1978	-0.87	-1.30	-2.16	-0.02	0.03	-0.78	-1.64	
1979	-0.30	-0.57	-0.54	-1.59	0.36	0.26	0.19	
1980	-1.52	-0.17	0.30	-0.57	-0.22	0.65	1.38	
1981	-0.72	-0.38	-1.00	0.06	0.24	0.40	-1.16	
1982	1.00	0.17	0.97	-2.21	2.87	0.65	1.58	X
1983	0.06	0.26	0.99	0.40	-0.44	1.47	0.27	
1984	0.43	-1.27	-0.60	0.70	-1.09	1.01	-0.95	
1985	-0.11	-1.81	-0.95	-0.74	-0.65	1.04	1.58	
1986	0.50	-0.85	-0.49	-0.36	0.94	1.80	0.97	
1987	0.91	-0.45	-0.39	0.31	0.60	1.15	0.28	
1988	0.33	2.69	1.70	1.63	-1.26	-0.80	-1.40	
1989	-0.25	1.25	0.55	0.52	-0.15	-0.39	-1.04	
1990	1.12	0.37	0.72	0.47	0.02	-1.81	-0.78	
1991	0.29	1.10	1.17	-1.45	1.32	0.15	0.53	X
1992	0.71	1.77	1.23	-1.30	0.08	0.26	-0.68	
1993	-1.13	-0.42	0.16	0.18	0.06	0.96	-0.48	
1994	1.01	0.72	0.70	-1.51	0.73	-0.61	0.68	
1995	-1.13	-1.05	-1.04	-0.30	-0.63	0.50	0.05	
1996	0.97	-0.10	-0.13	0.28	-0.70	0.16	0.07	
1997	1.14	-0.78	-0.36	-1.90	3.00	1.02	1.03	
1998	1.89	0.65	0.35	1.57	-0.95	-0.47	-0.56	
1999	0.39	1.13	0.84	0.37	-1.29	-1.49	-0.32	
2000	0.29	-1.31	-0.69	0.60	-0.44	0.47	0.50	
2001	2.93	0.45	-0.34	0.57	-0.31	-0.43	-0.46	
2002	-1.12	-0.65	-0.70	-0.70	0.81	1.98	0.71	

	Positive Anomaly
	Negative Anomaly

6.2.2 MONTREAL ANALYSIS

The positive phase of ENSO induced a positive temperature anomaly in 1982 and 1997. The El Nino events that transpired these two years disrupted the mean global circulation, (e.g., Fedorov et al., 2000). Although Nino3 SST correlates quite poorly with Montreal winter temperatures following the climate shift, (0.01), these two events were of substantial magnitude, (as seen by the two largest positive peaks in Figure 5.6) that they overrode the observed trend seen in Table 5.6. During an El-Nino event there is an excess build up of energy in the eastern tropical Pacific Ocean. Energy is transported poleward via a chain of complex atmospheric interactions and feedback mechanisms. Weather patterns are considerably altered across the Northern Hemisphere. The sub-tropical and polar jet streams are modified, (NOAA, 2004c). The resultant stronger subtropical jet stream flows into the United States advecting mild Pacific air across the United States and diverts the polar jet stream further north into Northern Canada. Consequently, southern Quebec finds itself in line with anomalously warmer surface air temperatures. Similarly during an El Nino the Aleutian low deepens substantially. This is in agreement with Mantua et al. [1997] who stated that the average wintertime Aleutian low positively correlates with the Southern Oscillation Index. This deepening likely overrides any weakening of the Aleutian low that may have ensued as a result of the positive PNA and PDO indices that were also observed in 1982 and 1997. Any cooling effects that may have resulted in Montreal as a result of the positive PNA and PDO indices were likely also dampened. Warmer air masses from southern latitudes are steered into most of Canada and the northwestern US, leading to milder winters during El Nino episodes, (McPhaden, 2000).

Figure 6.10 is a basic cartoon that demonstrates the effect an El Nino has on global temperature and precipitation during a northern hemisphere winter. Most of Quebec finds itself in a region of warmer surface air temperatures, (red shading).

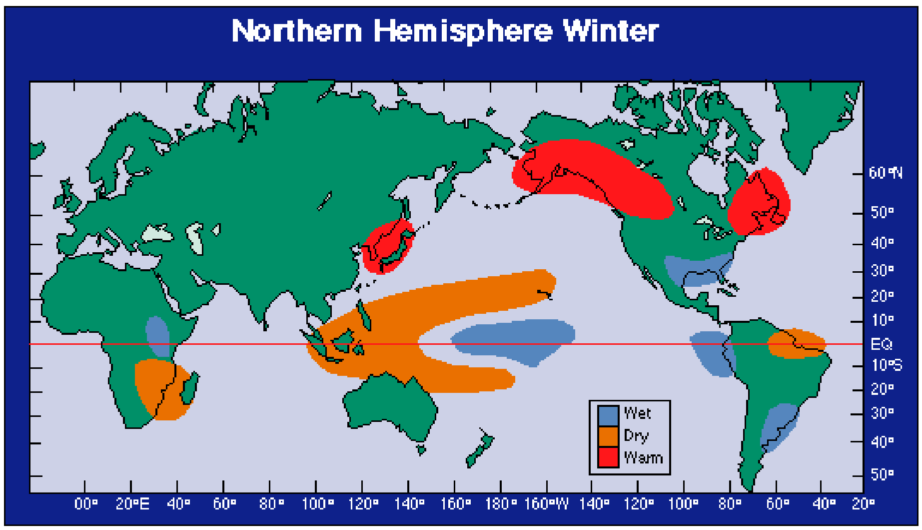

Figure 6.3 Effects of El Nino on Winter Temperature and Precipitation (NOAA, 2004d)

In 1990, 1994 and 1998, three years of positive temperature anomalies at Montreal, a positive PDO index (1990), a positive NOI index (1994) and a negative NOI index (1998) were observed. PDO however correlates negatively with winter temperature at Montreal. Table 5.4 indicates that NOI does not correlate well with Montreal winter temperature after 1976. The warmer temperature anomalies in these three years were likely due to concurrent, slightly weaker NAO indices in 1990 and 1994, (0.72 and 0.7) and AO indices in 1994 and 1998, (0.72, 0.65). Generally a positive AO index, (Figure

2.1) coincides with relatively low pressure over the polar cap (e.g., Folland et al., 2000) trapping cold air high into the arctic regions, leaving warmer air to the south. This was seen in 1974. In combination with a southerly flow from the western flank of the Azores/Bermuda high, it acted to increase winter temperatures. When NAO is positive, (Figure 2.2) the Icelandic low deepens and the Azores/Bermuda high strengthens. This combination consequently leads to a stronger more zonal jet stream across the North Atlantic, advecting cool air away from the continent. Because the Azores/Bermuda high more expansive, it is able to divert the polar jet stream higher north preventing cold polar air from plunging southward into Southern Quebec. Montreal is situated so as to receive a warmer southerly flow off the western portion of the Azores/Bermuda high. Surface air temperatures in these three years were subsequently warmer.

In 2001 the positive temperature anomaly observed at Montreal did not relate to strong atmospheric circulation regimes. Although the individual indices were relatively small in magnitude, AO was in a positive phase with an index value of 0.45. PDO and PNA were in negative phases with index values of –0.43 and –0.46. As stated above a positive AO index may lead to positive surface air temperature anomalies at Montreal. The weakening of the Aleutian low inherent in the negative phase of PDO prevents distortion of the zonal mean winds across North America, inhibiting the development of deep lows over Quebec. Similarly winds are also more zonal during the negative phase of the PNA, and the characteristic low-pressure system in western North America and the high-pressure system found over the southeastern United States may act to draw warmer air into southern Quebec.

Montreal experienced anomalously cooler temperatures in 1977, 1980, 1993, 1995 and 2002. In 1977 and 1995 negative NAO and AO indices were observed. Associated with negative AO episodes is a weak, more disorganized polar vortex, (Baldwin and Dunkerton, 2001). This gives rise to a weaker westerly flow of air from the Pacific Ocean and an increased northerly flow of arctic air into central and eastern Canada, encompassing Montreal.

During the negative NAO index seen in 1995 the Icelandic low weakens and the Azores high is displaced south. A high-pressure system may develop between in the North Atlantic known as the Greenland Anticyclone, (Greatbatch, 2000). Although it is unclear as to whether this anticyclone contributes to low index periods of NAO or is merely a symptom of the weakened polar vortex often associated with low index, the prevailing westerlies are blocked preventing frigid continental air from exiting North America. The cold air collects and spreads south over the eastern Canada and United States. The combined effects of the weakened polar vortex allowing cooler air to plunge southward and the Greenland Anticyclone preventing the escape of cold air from the continent placed Montreal in a trough of cold air.

In 1977 the cooling effects of the negative AO index were aided by a positive PNA index. When PNA is positive (Figure 2.4), the eastern portion of the United States finds itself surrounded by a low-pressure system. To the west of the low, is a high. Dry continental polar air pooled in from the northwestern (northeastern) portion of the low (high) acts to cool much of southern Quebec. A positive PNA index was also observed in 1980. In 2002 a positive PDO index contributed to the anomalously cooler winter temperatures at Montreal. A positive PDO index acts to deepen the Aleutian low and thus distort the more average zonal wave train usually present across Canada, causing the creation of a trough further east over Quebec.

In 1993 anomalously cooler surface air temperatures were recorded, however there were no anomalous large-scale atmospheric circulation regimes occurring concurrently. In 1991, the eruption of Mount Pinatubo occurred. It is widely believed that this can explain the unusual cooling seen in the winter of 1993, (e.g., Robock et al., 1995).

6.2.3 INSIGNIFICANT TEMPERATURE ANOMALIES

As was seen at Fairbanks, the primary reason for temperature anomalies that were less than one standard deviation from the mean occurring simultaneously with anomalous large-scale regimes are dampening effects among competing large-scale circulation regimes. Dampening effects due to volcanic activities were not as important as observed at Fairbanks.

6.3 DISCUSSION

The following discussion compares and contrasts the effects that the large-scale atmospheric circulation regimes found in this study have on winter surface air temperature at Fairbanks and Montreal from 1977 to 2002.

Fairbanks experienced six years with anomalously strong winter surface air temperatures and Montreal experienced eleven years of anomalously strong winter surface air temperatures. Anomalous temperatures are defined as those exceeding one standard deviation from the mean.

Table 6.3 presents a summary of how the large-scale indices examined in this study are associated with positive or negative winter temperature anomalies at Montreal and Fairbanks. Each relevant index is highlighted in blue, (positive) or in yellow, (negative) according to the sign associated with the observed temperature anomaly.

Table 6.3 Summary of the Large-Scale Indices and their Signs

Positive Temperature		Negative Temperature	
Montreal	Fairbanks	Montreal	Fairbanks
AO	AO	AO	
NAO		NAO	
Nino 3			Nino 3
PDO	PDO	PDO	
PNA	PNA	PNA	
			NOI

	Positive Index
	Negative Index

An anomalous index may result in temperature anomalies of opposite signs at Fairbanks and Montreal. This is seen in Table 6.3 when PDO and PNA is positive or when AO is negative. PDO and PNA indices correlate negatively with winter temperatures in Montreal (Table 5.4), therefore when the indices are positive, negative temperature anomalies at Montreal may be expected. On the other hand, PDO and PNA correlate positively (Table 5.3) with winter temperatures at Fairbanks generally implying that the positive phases of PDO and PNA may lead to anomalously warmer temperatures at Fairbanks. The deepening of low-pressure systems in the Pacific, off the west coast of North America inherent to positive PDO and PNA indices advects warmer air into Alaska and at the same time distorts the normally more zonal mean winds across North America. This distortion leads a meridional wave pattern that may place southern Quebec in a trough of cooler air. A negative AO index has a similar effect. The weakened, more disorganized polar vortex creates a trough of cool air in the eastern Arctic, while placing the western Arctic in a ridge of high pressure, accompanied by anomalously warmer temperatures.

In 1995 and 1998 Montreal and Fairbanks experienced anomalous temperatures concurrently. Negative temperature anomalies were observed at both cities in 1995 coinciding with negative AO and NAO indices and a La Nina event. The anomalous temperatures at each city were not associated with the same indices. Comparing the strengths of the negative AO and NAO indices (-1.05 to –1.04) to that of the La Nina (-0.63) and the closer proximity of Montreal to the centers of action of AO and NAO indicate that it is highly likely that the negative AO and NAO indices were the primary indices associated with the anomalously cool temperatures at Montreal. Table 5.3

indicates that AO and NAO correlate negatively with winter temperatures at Fairbanks. It is therefore unlikely that these two indices, in a negative phase directly contributed to the anomalously cool temperatures at Fairbanks in 1995. The La Nina event that occurred the same year was the primary index that led to the negative temperature anomaly.

In the winter of 1998 Montreal experienced anomalously warm temperatures and Fairbanks experienced anomalously cold temperatures. A positive NOI index and a somewhat weaker positive AO index occurred simultaneously. The NOI likely did not impact temperatures at Montreal during winter of 1998. Table 5.3 indicates that following the climate shift the relationship between NOI and winter temperature at Montreal drops dramatically. The positive temperature anomaly at Montreal can be associated with the positive AO index. On the other hand, NOI remains the primary index leading to anomalously cool temperatures at Fairbanks that same year. The positive AO index may have been associated with the negative temperature anomalies at Fairbanks in 1998, but the somewhat lower index value of 0.65, may categorize its involvement as secondary.

From 1977 to 2002 Montreal experienced twice as many anomalous winter temperatures than Fairbanks. Overall, there are more indices affecting winter surface air temperature in the eastern Arctic than in the western Arctic. The combined effects of NAO and AO may also explain why a greater number of temperature anomalies occurred in Montreal over the 26-year period. The centers of actions of NAO and AO are closer to the Atlantic and often have a greater influence on winter temperatures in the eastern Arctic rather than in the west. Furthermore, some of these years, in which AO and NAO indices were observed were accompanied by competing anomalous PDO, PNA or NOI indices that ultimately dampened the effects that they may have had on temperature at

Fairbanks. Finally, volcanic activity seems to have had a greater impact on dampening the effects of simultaneously occurring anomalous indices at Fairbanks rather than Montreal.

CONCLUSION AND FUTURE WORK

The relationships between six large-scale atmospheric circulation regimes and winter surface air temperature in the North American Arctic have been presented in this study. Some of the regimes influence the western and eastern regions of the North American Arctic differently; therefore we have examined surface air temperatures at both Fairbanks (west) and Montreal (east).

Analyses done in this study has focused on the years following the 1976-1977 climate shift. Six years of the 26 years had anomalous winter surface air temperatures at Fairbanks. PDO, PNA, ENSO, NOI and AO were important in causing temperature anomalies at Fairbanks. Eleven years of the 26 years had anomalous winter surface air temperatures at Montreal. AO, NAO, PDO, PNA and ENSO had strong associations with temperature anomalies at Montreal. While strong relationships of winter surface air temperature to large-scale circulation regimes were seen at both cities during these anomalous years, there were more instances of anomalous indices affecting winter surface air temperature at Montreal, associated with its closer proximity to the centers of actions of NAO and AO. In addition, years where anomalous large-scale atmospheric circulation regimes were observed, yet winter surface air temperature remained unaffected were more frequently observed at Fairbanks rather than Montreal. Opposing effects that two or more large-scale atmospheric circulation regimes have on surface air temperature there, leading to neutral, or insignificant temperature anomalies, may explain these circumstances. At Fairbanks when PDO, PNA and NOI were in competing phases, no surface air temperature anomalies were apparent. Dampening effects due to the influence that volcanic activity has on tropospheric circulation may also be associated with the greater number of insignificant temperature anomalies observed in the western Arctic as compared to the eastern Arctic. The eruption of Mount Pinatubo in 1991 has been associated with positive AO indices during the following two winters.

There were two years where anomalous temperatures were observed at both cities simultaneously. This study has shown that the concurrent temperature anomalies in 1995 and 1998 were likely caused by different large-scale atmospheric circulation regimes. This may be due to the geographic proximity of the centers of actions of the indices to each city.

The results from this research provide the foundation for the future construction of a statistical prediction model for seasonal surface temperature variations in the North American Arctic. In order to continue with a modeling study additional preliminary research is needed. Years in which large-scale circulation regimes did not produce significant temperature anomalies should be further understood. Furthermore, examining monthly data versus seasonal data would prevent the loss of important temperature anomalies caused by smoothing, adding more data into the study. A non-linear approach should also be taken into consideration.

Investigating the more detailed impacts that the climate shift may have had on arctic temperatures may also prove useful and may further explain why the eastern Arctic experienced more temperature anomalies than the western Arctic. The inclusion of additional locations representing a larger expanse of the Arctic may answer some more questions pertaining to the connectivity of large-scale regimes across the Arctic and would certainly provide more insight into how and why surface temperature anomalies occur.

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