Forests **2015**, *6*, 2762-2784; doi:10.3390/f6082762

OPEN ACCESS

forests

ISSN 1999-4907

www.mdpi.com/journal/forests

Article

Influence of Low Frequency Variability on Climate and Carbon Fluxes in a Temperate Pine Forest in Eastern Canada

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Academic Editor: Eric J. Jokela

Received: 10 June 2015 / Accepted: 31 July 2015 / Published: 12 August 2015

Abstract: Carbon, water and energy exchanges between forests and the atmosphere depend upon seasonal dynamics of both temperature and precipitation, which are influenced by low frequency climate oscillations such as: El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Eastern Pacific Oscillation (EPO) and the Pacific-North American (PNA). This study investigated the influence of climate oscillations on the local climate and carbon fluxes in a 75-year old temperate pine (*Pinus strobus* L.) forest, near Lake Erie in southern Ontario, Canada. Analyses indicated mean winter temperatures were correlated to NAO, AO and EPO, total winter precipitation was influenced by PNA and AO, while total snowfall was correlated with PNA and ENSO. These impacts influenced carbon dynamics of the forest during the winter and spring seasons. The EPO had a significant inverse correlation with winter and spring carbon fluxes, while the Pacific Decadal Oscillation (PDO) was significantly correlated with winter respiration. In 2012, an extreme warm event linked to climate oscillations raised temperatures and resulted in a large release of carbon from the forest due to higher ecosystem respiration. As low frequency climate oscillations are important drivers of extreme weather events, affecting their intensity, frequency and spatial patterns, they can cause large changes in carbon exchanges in forest ecosystems in the northeastern parts of North America.

Keywords: climate variability; low frequency climate signals; net ecosystem productivity; eddy covariance; *Pinus strobes* L.; temperature conifer forest

1. Introduction

Forests are considered an important sink for atmospheric carbon dioxide (CO_2) and have the potential for temporarily storing atmospheric CO_2 in terrestrial ecosystems to offset anthropogenic greenhouse gas emissions. Past studies have shown that the forest carbon (C) cycle responds to climate variations [1–3]. Therefore, predicted future climate changes may have a severe impact on forests ecosystems. While a warming-induced increase in the growing season length [4], CO_2 fertilization and higher nitrogen deposition effects are expected to increase C assimilation in the future [5,6], the short-term effects through extreme climatic events such as droughts, flooding, heatwaves, duration and timing of the winter and freeze/thaw periods, as well as disturbance regimes are expected to severely affect forests [7–12].

In North America, low frequency climate oscillations, such as the El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the Pacific Decadal Oscillation (PDO), the Eastern Pacific Oscillation (EPO) and the Pacific-North American (PNA) teleconnection pattern, are important atmospheric phenomena that influence seasonal and annual climate variations [13–16]. Timescales of these oscillations range from interannual to interdecadal, and their impacts are typically stronger during the winter months but can persist into the spring and summer months.

In the Great Lakes region, both the western (ENSO, PDO, EPO and PNA) and eastern (NAO and AO) low frequency oscillations, are known to be influential, and may influence the amount and type of winter precipitation [17,18]. Additionally, during the winter months, these oscillations can impact the presence or absence of ice cover in the Great Lakes [19,20], which are known to have significant effects on both regional climate and weather events [20]. These changes in regional climate may have an impact on the growth and carbon uptake in vegetation ecosystems, in particular forest ecosystems, which are re-establishing in this region as re-growth on abandoned agricultural lands or plantations. These re-emerging forests of North America are a large sink of carbon [21,22]. Changes in atmospheric circulation associated with these oscillations can lead to changes in seasonal temperatures and precipitation patterns, and hence can result in changes to the forest carbon exchange.

ENSO is a coupled ocean-atmosphere interaction that occurs across the equatorial Pacific Ocean [23]. It consists of a warm (El Niño) and a cold episode (La Niña), lasting from six to 18 months, with neutral years interspersed between the episodes. El Niño (La Niña) episodes often brings less (more) precipitation and warmer (cooler) conditions to a majority of North America [13,24]. Higgins *et al.* [25] suggested that although La Niña events generally bring colder temperatures to most of Canada, since the Pacific jet stream is displaced northward; there is a decrease in the frequency of Arctic air intrusions into the Great Lakes region which impacts lake ice cover. In this region, a non-linear relationship exists between ENSO and Great Lakes ice cover as a majority of the maximum ice covers have occurred during weak or neutral ENSO episodes, whereas most of the minimal ice covers have occurred during strong El Niño or La Niña events [18]. Due to this non-linear response, strong ENSO events (both strong El Niño and La Niña episodes) have generally produced warmer winter temperatures and more or less winter precipitation, depending on the location [26–28]. Assel *et al.* [29] observed that lower winter precipitation due to El Niño events generally occurred in the upper Great Lakes region, whereas the lower lakes, such as Lake Erie, observed an opposite effect. LaValle *et al.* [30] found that Lake Erie water levels were significantly correlated with ENSO, as El Niño (La Niña) episodes were often associated with higher (lower) water levels, although the response of lake levels to precipitation can take anywhere from three months to two years [31]. Generally, strong El Niño (La Niña) episodes produce dry (wet) winter seasons in this region.

The PDO is a low-frequency oscillation, which characterizes the interannual variability in the average North Pacific sea-surface temperature [32]. Warm (cold) phases exist with the PDO, often associated with below- (above-) average precipitation and warmer (colder) temperatures in northwestern North America but without neutral phases [32]. The PDO has a much longer cycle than ENSO, persisting for two to three decades, while a typical ENSO event can persist for six to 18 months [33] but can influence ENSO events by enhancing or suppressing the strength of their signals. Gershunov and Barnett [34] found that El Niño (La Niña) signals were stronger and stable during positive (negative) PDO events. Over the Great Lakes region, positive (negative) phases on the PDO usually produce cooler (warmer) and drier (wetter) conditions.

The PNA pattern is a dominant mode of atmospheric variability over North America and strongly influenced by the ENSO phase (positive phase associated with an El Niño episode), and has been observed at time scales ranging from days to decades [35–37]. As with the PDO, positive (negative) phases of the PNA produce cooler (warmer) and drier (wetter) conditions in the Great Lakes region.

The EPO has centers of action at 500 hPa height fields [38,39]. The positive phase is represented by a ridge east of Hawaii and a trough in the Gulf of Alaska, with a secondary ridge near Hudson Bay [40]. During a positive EPO phase, the Great Lakes region tends to have cooler conditions, while the negative phase is associated with warmer temperatures (National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center).

The NAO is associated with changes in the surface westerly winds across the Atlantic and into Europe. It is an oscillation of atmospheric pressure at sea level between the Icelandic Low and the Azores High [41]. The AO is the mass exchange between the Arctic Ocean and the middle latitudes. It resembles the NAO in many respects, but covers more of the Arctic [42]. A positive phase of the NAO and AO generates warmer and wetter conditions, while a negative phase is expected to make the Great Lakes region generally cooler and drier.

Previous studies have shown that low frequency climate oscillations can have a strong influence on extreme climatic events [43–46]. Summer and winter climate extremes have been linked to climate oscillations. Loikith and Broccoli [47] found that extreme warm and cold temperatures were strongest between the PNA and AO in regions most influenced by these teleconnections, with a weak association with ENSO events. For example, during negative AO events, there is an increase in the probability of extreme cold minimum temperatures over the northeastern part of North America. Summertime associations were weaker than wintertime associations due to influences on the local surface energy budget, such as soil moisture, and circulation patterns are smaller in scale and weaker in magnitude than in the winter. Ning and Bradley [45,46] found similar results for winter temperature and precipitation extremes; however, they noticed that maximum and minimum values were not as sensitive to climate variability as the mean values. Current sea-ice conditions also influence the NAO and AO, which may lead to changes in the weather patterns around the Great Lakes region, and increased probability of extreme climatic events [48–50].

Several studies have tried to identify links between ENSO and NAO [51–54]. Both the ENSO and NAO create a combination of influences by increasing or decreasing temperatures and/or the amount of precipitation, depending on the region. Interference of these low frequency climate oscillations may have profound impact on the climate and forest ecosystems in the northeastern North America and Great Lakes region, particularly during the winter. The simultaneous occurrence of two or more of oscillations can exaggerate impacts of seasonal and annual climate variability on carbon, water and energy fluxes in the forest ecosystems in the region. Extreme events, such as heatwaves, droughts or flooding, can partially offset carbon sinks or even cause net losses of carbon in forest ecosystems. Forest ecosystems, although potentially susceptible to all types of extreme events, are particularly vulnerable to drought [12], where the effects on the carbon balance can be both immediate and lagged, and potentially long-lasting. Since large-scale modes of climate variability are important drivers of changes in climate extremes [43], changes to these modes will affect the intensity, frequency and spatial patterns of extreme climatic events, leading to changes in carbon fluxes in forest ecosystems [55].

In this study, we investigate the occurrence and impacts of several low frequency climate oscillations in the Great Lakes region in Canada over the past six decades (1950–2014). The specific objectives are to (i) determine correlation between each low frequency climate oscillation and temperature, precipitation and snowfall in the Great Lakes region from 1950 to 2014 and (ii) quantify changes in gross ecosystem productivity (GEP), ecosystem respiration (Re) and net ecosystem productivity (NEP) due to low frequency climate oscillations in a temperate pine forest in the region, using measured eddy covariance flux data from 2003 to 2014.

2. Study Area

The study area is a 75-year old eastern white pine forest near Turkey Point Provincial Park on the northern shore of Lake Erie in Southern Ontario, Canada (Figure 1). This site is part of Turkey Point Flux station (TPFS) as well as and the global Fluxnet initiatives. The topography at the site is fairly flat with well drained sandy soil (Brunisolic Gray Brown Luvisol, following the Canadian Soil Classification system), which is composed of ~98% sand, 1% silt, and 1% clay.

The forest was planted in 1939 on cleared oak-savanna lands to stabilize soils, which has lead to a nearly homogeneous canopy height and structure [56]. Tree composition is 82% white pine (*Pinus strobus* L.), 11% balsam fir (*Abies balsamea* L. Mill) and native Carolinian species including 4% oak (*Quercus velutina* L., *Q. alba* L.) and 2% red maple (*Acer rubrum* L.). The average tree height is 21.8 ± 1.7 m, and stand density is about 421 ± 166 stems·ha^{-1}. Our forest is managed by the Ontario Ministry of Natural Resources and Forestry, and currently is in the preparatory stage of development under the shelterwood silvicultural system [57]. This system is characterized by two or more partial thinnings over a few decades to allow for regeneration and development of seedlings in partial shade. The first cut was applied in 1983 and the second in the winter of 2012. In both thinnings approximately 30% of the trees were removed to improve light and water availability, and stimulate growth of the remaining trees. Further site details can be found in [56–60]. The climate in the region is cool-temperate with a 30-year mean annual temperature of 8.0 °C, and mean annual precipitation of 1036 mm, with

83% falling as rain (based on 1935–2014 Environment Canada weather data for Delhi, Ontario, located about 25 km to the northwest of forest).

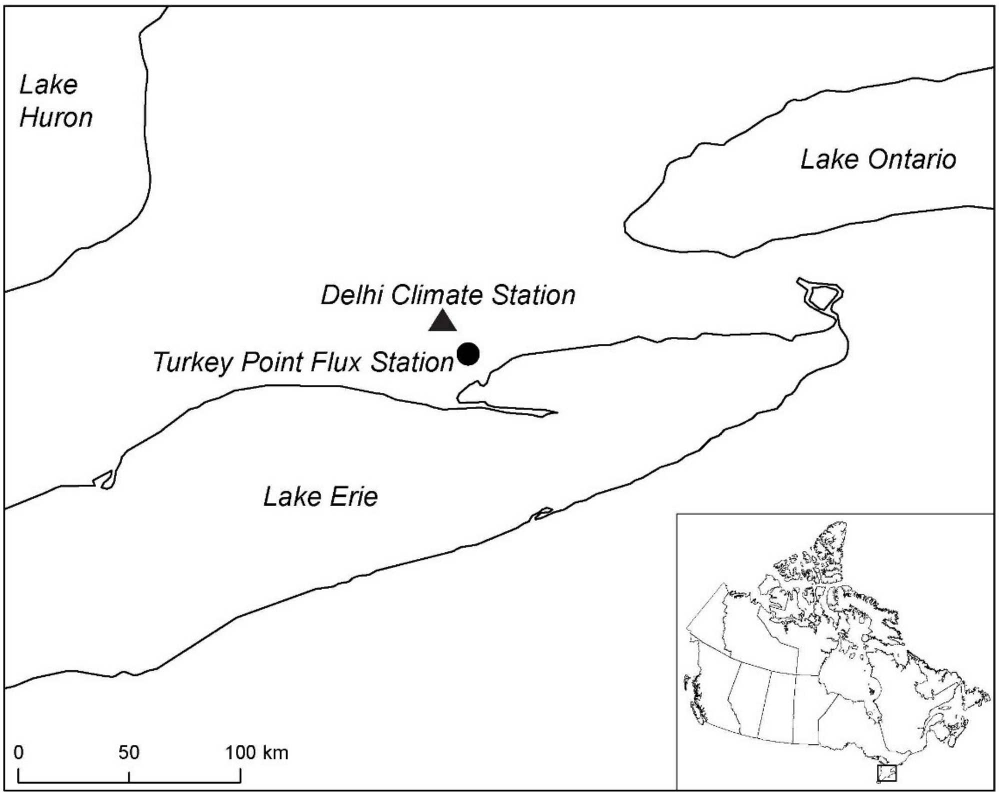

Figure 1. Location of the Turkey Point Flux station on the north shore of Lake Erie in Southern Ontario, Canada. The location of closest (25 km away) long-term climate station at Delhi maintained by Environment Canada is also shown.

3. Data and Methods

Water, carbon and energy fluxes were measured using a closed-path eddy covariance system, comprising of a sonic anemometer (CSAT3, Campbell Scientific Inc. (CSI), Edminton, AL, Canada) and infrared gas analyzer (Li-7000, LI-COR Inc., Lincoln, NE, USA). Flux measurements were made at 20 Hz above the canopy at 28m on top of a scaffolding tower. Climate variables were also measured including air temperature, relative humidity, windspeed and direction, atmospheric pressure and precipitation. Precipitation was measured in an open area 2 km northeast of site, using a weighed accumulation rain gauge (T200B, Geonor Inc., Augusta, NJ, USA) and a complimentary tipping bucket rain gauge (TE525, Texas Inst., Dallas, TX, USA). All flux and meteorological data were quality controlled and averaged at half hourly intervals. Further details of closed-path eddy covariance systems and meteorological and soil measurements are described in [56–60].

To investigate the possible linkages of regional climate with large-scale atmospheric variability, Pearson correlations were conducted between the various oscillation indices described in Section 1 and climate variables (mean temperature, total precipitation and total snowfall) from the climate station in Delhi, Ontario spanning the years 1950 to 2014. These oscillation indices are created based on the differences between the relative controlling variables for each oscillation (e.g., sea surface temperature, air pressure) and were obtained from the National Oceanic and Atmospheric Administration Climate Prediction Center (NAO index and PNA index), the Bureau of Meteorology (ENSO, as the Southern Oscillation Index), and the Joint Institute for the Study of the Atmosphere and Ocean (PDO index and EPO index). For all analysis, only winter index values (averaged between November to March) were used, as these climate signals are notably stronger in the winter. A linear correlation was still applied when using the SOI to keep the methodology consistent with the other teleconnections. Carbon fluxes, local climate and climate oscillations from 2003 to 2014 were used in this analysis. Seasons were classified as winter (November to March), spring (April and May), summer (June to August) and fall (September and October).

Determining the strength of an oscillation depends on the oscillation itself and how it is defined. For this study, positive (negative) moderate to strong phases/events were defined as those years that fall into the upper (lower) quartile of the data set. The years found in the mid-quartile range were considered to be in a neutral phase. A short-term analysis, from 2003 to 2014, was conducted to determine the strengths and phases of each oscillation for each year, and then their effects on climate and carbon fluxes.

4. Results and Discussion

The relationship between the climate oscillations and climate variables from the long-term climate station data is first analyzed, followed by a breakdown of the strengths of each oscillation, for the years 2003 to 2014, and their potential impact on the local climate and carbon fluxes at the forest site.

4.1. Long-Term Analysis

In the Great Lakes region, past studies have shown that both eastern and western oscillations influence the local climate and these impacts are stronger in winter season [17–19]. Each year, four possible conditions can occur depending on the strength of the various oscillations over the winter season: (1) only one strong oscillation occurring for that winter, overpowering all other oscillations; (2) two or more strong oscillations; (3) strong oscillation(s) combined with regional effects (such as lake effect) and (4) only weak to neutral phases of these oscillations, where regional effects are more noticeable. When only one oscillation is strong, its phase/event will generally be the most influential on the local climate. When two or more oscillations are strong, both may impact at the same time or they may be out of phase in terms of their effect on the region, with the possibility of their influences being nullified by each other. For example, Bai *et al.* [60] found that during the 2009/2010 winter season over the Great Lakes region, a negative AO, which generally brings cooler temperatures, coincided with a strong El Niño event that typically is associated with warmer temperatures. The ENSO event dominated the mid latitude and prevented cold Arctic air mass from intruding from the north, leading to a warmer winter. Additionally, with the combination of the PNA, PDO and ENSO oscillations, which are highly correlated with each other, Ning and Bradley [50] have shown that with strong PNA and PDO events, those years with and without ENSO forcing have a different impact on moisture flux patterns over the northeastern United States.

Our analysis showed a positive correlation between mean winter temperature and the NAO (0.33, with significance at the 99% confidence level) and AO (0.29, with significance at the 95% confidence level) indices, while it showed a negative correlation with the EPO (−0.48, with significance at the 99%

confidence level) index (Table 1). These significant correlations confirm that positive (negative) phases of the NAO and AO can increase (decrease) winter temperatures in the region, where the opposite is true for the EPO. The PNA and AO indices both had a significant correlation with total winter precipitation (−0.37 and 0.29, with significance at the 99% and 95% confidence levels), where a negative (positive) phase of the PNA and a positive (negative) phase of the AO brought more (less) winter precipitation to the area. The EPO index has a significant positive correlation (0.30, with significance at the 95% confidence level) with autumn precipitation, increasing precipitation during positive phases. Only the PNA and SOI indices showed a significant correlation with total winter snowfall (−0.34 and −0.33, with significance at the 99% confidence level), where negative (positive) phases of the PNA generally produce more snowfall, and El Niño (La Niña) events decrease (increase) total snowfall amounts. Correlations between the PNA index and winter precipitation is consistent to those findings by Coleman and Rogers [61] for the Ohio River Valley. No significant correlations were found between the oscillation indices and spring, summer and autumn temperature, and spring and summer precipitation.

Table 1. Correlation between each climate oscillation and seasonal temperature, precipitation and total snowfall from 1950 to 2014.

Season	PDO	PNA	ENSO	NAO	AO	EPO
			Temperature			
Winter	−0.23	−0.02	−0.12	0.33 **	0.29 *	−0.48 **
Spring	−0.18	0.15	−0.05	−0.13	−0.23	−0.13
Summer	0.08	0.12	−0.14	0.19	0.10	−0.19
Autumn	0.03	0.12	−0.09	−0.07	−0.06	−0.15
			Precipitation			
Winter	−0.23	−0.37 **	0.09	0.19	0.29 *	−0.13
Spring	−0.08	−0.10	0.08	−0.09	−0.12	0.15
Summer	0.02	0.06	−0.10	0.20	0.14	−0.13
Autumn	0.22	0.17	−0.03	0.08	−0.01	0.30 *
			Snowfall			
	−0.15	−0.34 **	0.33 **	−0.03	0.08	0.02

* and ** indicate significance at the 95% and 99% confidence levels. PDO: Pacific Decadal Oscillation , PNA: Pacific-North American , ENSO: El Niño-Southern Oscillation , NAO: North Atlantic Oscillation , AO: Arctic Oscillation , EPO: Eastern Pacific Oscillation.

4.2. Occurrence, Strengths and Impacts of Climate Oscillations

Mean winter time series of each oscillation from 1950 to 2014 is shown in Figure 2, with the last twelve years highlighted by a grey box. Strong to moderate phases/events of each oscillation are denoted by the upper and lower quartile of that particular oscillation. ENSO events have fluctuated between El Niño or La Niña episodes, with four strong events (three La Niña and one El Niño) occurring between 2007 and 2011 (Figure 2). The PDO was strongly positive in 2002/2003 and 2003/2004, and strongly negative in 2008/2009, 2010/2011 and 2011/2012. The PNA was also strongly positive in 2002/2003 and in 2009/2010. Strong negative events of the PNA occurred in 2008/2009 and 2011/2012. A strong positive EPO event occurred in 2002/2003 and 2013/2014, with strong negative events in the 2007/2008, 2009/2010 and 2011/2012 winters. The NAO was strongly positive in 2003/2004, 2006/2007, 2007/2008, 2011/2012 and 2013/2014, with just two strong negative events in 2009/2010 and 2010/2011. The AO had strong positive events in 2006/2007, 2007/2008, 2011/2012 and 2013/2014, with strong negative events in 2009/2010 and 2012/2013. It should be noted that there were no strong events observed during the 2005/2006 winter for any of the oscillations.

As previously discussed, the strength of an oscillation determines how influential it is in the Great Lakes region. Each oscillation has its own level of strength and the occurrence of more than one strong oscillation can complicate how the local climate responds (e.g. [19,60]). As the correlation between climate indices and seasonal variables show a stronger connection to the winter, this section will only focus on winter climate response to climate oscillation. Deviation of the mean winter temperature, precipitation and total snowfall, for each year from the long-term mean values (1935–2014) is shown in Figure 3. In 2002/2003, there were strong positive events of the PDO, PNA and EPO and an El Niño event (Figure 2); the first three generally produce cooler and drier conditions, where as the El Niño event typical produces warmer and drier conditions. It is most likely that the cooler conditions from the PDO, PNA and EPO will overpower warmer temperatures typically brought in by an El Niño event. Station data for the 2002/2003 season showed that, most likely, cooler conditions from the PDO, PNA and EPO overpowered warmer temperatures typically brought in by an El Niño event. Winter temperatures were cooler than the mean (−1.4 °C), and less precipitation and snowfall (−191 mm and −69 mm respectively) were observed (Figure 3). In 2003/2004, there was a strong positive PDO and NAO event, with a positive PDO event producing cooler and drier conditions, whereas a positive NAO event brings in warmer and wetter conditions. These conflicting events could result in one overpowering the other, or a mix of the two, neutralizing both their influences. Winter temperature and precipitation were slightly above the mean (0.4 °C and +30 mm), with total snowfall lower than normal (−44 mm). This year, the positive NAO more than likely had a stronger influence on the local climate. For 2004/2005, only a strong El Niño event occurred, however, winter temperatures were cooler (−0.6 °C), and winter precipitation and total snowfall were higher (+26 mm for both). Here, the El Niño event did not seem to have much influence on the local climate.

In 2005/2006, there were no strong oscillations present and, therefore, regional climate effects or possibly weak to moderate oscillation events could have been influencing factors. Winter temperatures were slightly warmer (1.4 °C), whereas winter precipitation was higher (+66 mm) and total snowfall lower (−29 mm). Average to warmer temperatures were found by Bai *et al.* [18], as ice cover over the Great Lakes was below normal. In 2006/2007, both the NAO and AO had strong positive events, which should bring warmer and wetter conditions to the area. Winter temperatures were warmer (1.0 °C), with more precipitation (+13 mm) and less total snowfall (−28 mm). In 2007/2008, a strong La Niña event, along with positive phases of the NAO and AO, and a negative phase of the EPO were present. All events combined would generally be expected to produce warmer and wetter winter conditions in the region. When examining the local climate during that winter season, temperatures were relatively close to their mean values (fractionally lower, −0.2 °C), while total winter precipitation and snowfall were much higher (+186 mm and +195 mm respectively). Ice conditions for the Great Lakes were found to be around normal by Bai *et al.* [18]. For 2008/2009, another strong La Niña event occurred, along with strong negative phases of the PNA and PDO. The same general response of a warmer and wetter season would be expected, but as with 2007/2008, this season had slightly cooler temperatures (−0.8 °C) and was much wetter than normal (+210 mm total precipitation and +103 mm snowfall). Wang *et al.* [17] found that the positive phase of the AO (which typically warms the region) behaved in an anomalous manner in this year. In mid-winter, the Icelandic Low deepened and split, with one section moving to the Labrador Sea. This movement brought cold, dry Arctic air into the Great Lakes region for both December and January. In late winter, the AO phase shifted back to a negative position. That is why the average index value for this year did not show a strong event occurring.

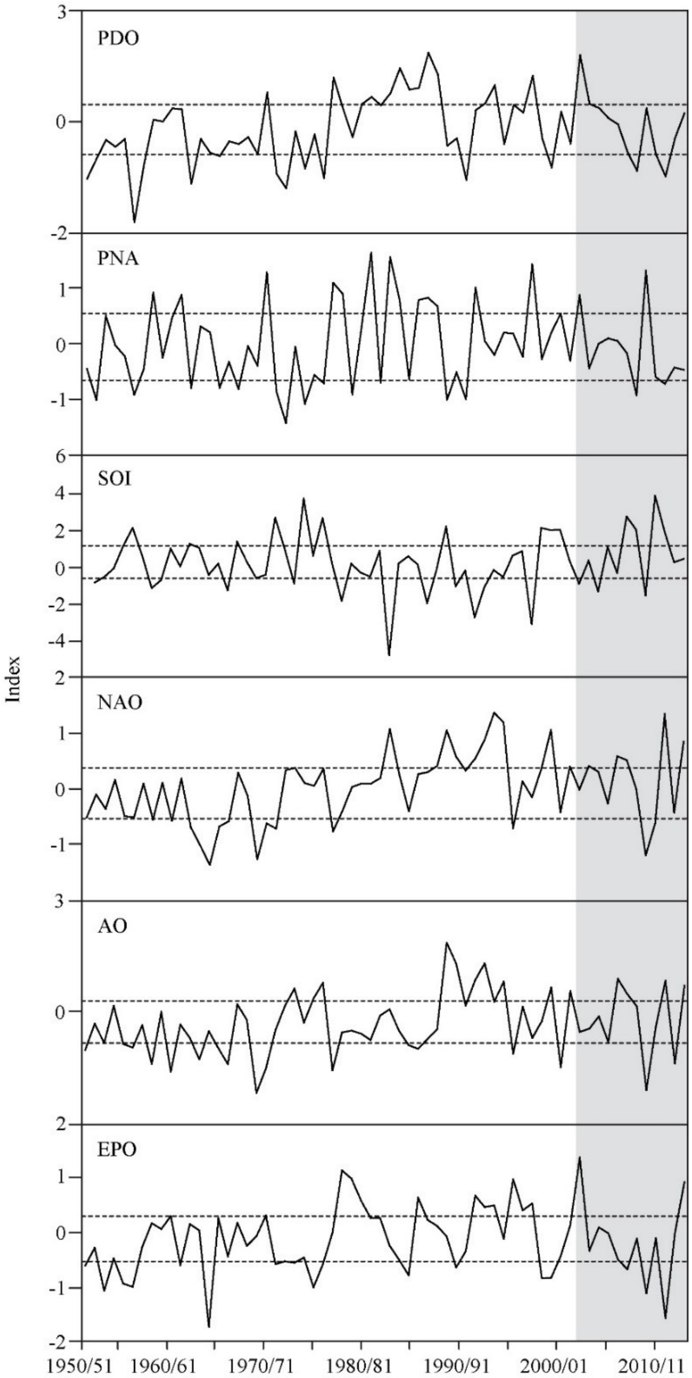

Figure 2. Time series of mean winter index values for each climate oscillation from 1950 to 2014. The last twelve years of the time series, within the grey box, are used for comparison with observed carbon flux data using the eddy covariance technique. Dotted lines for each oscillation are the upper and lower quartile thresholds used to determine which events/phases are moderate to strong.

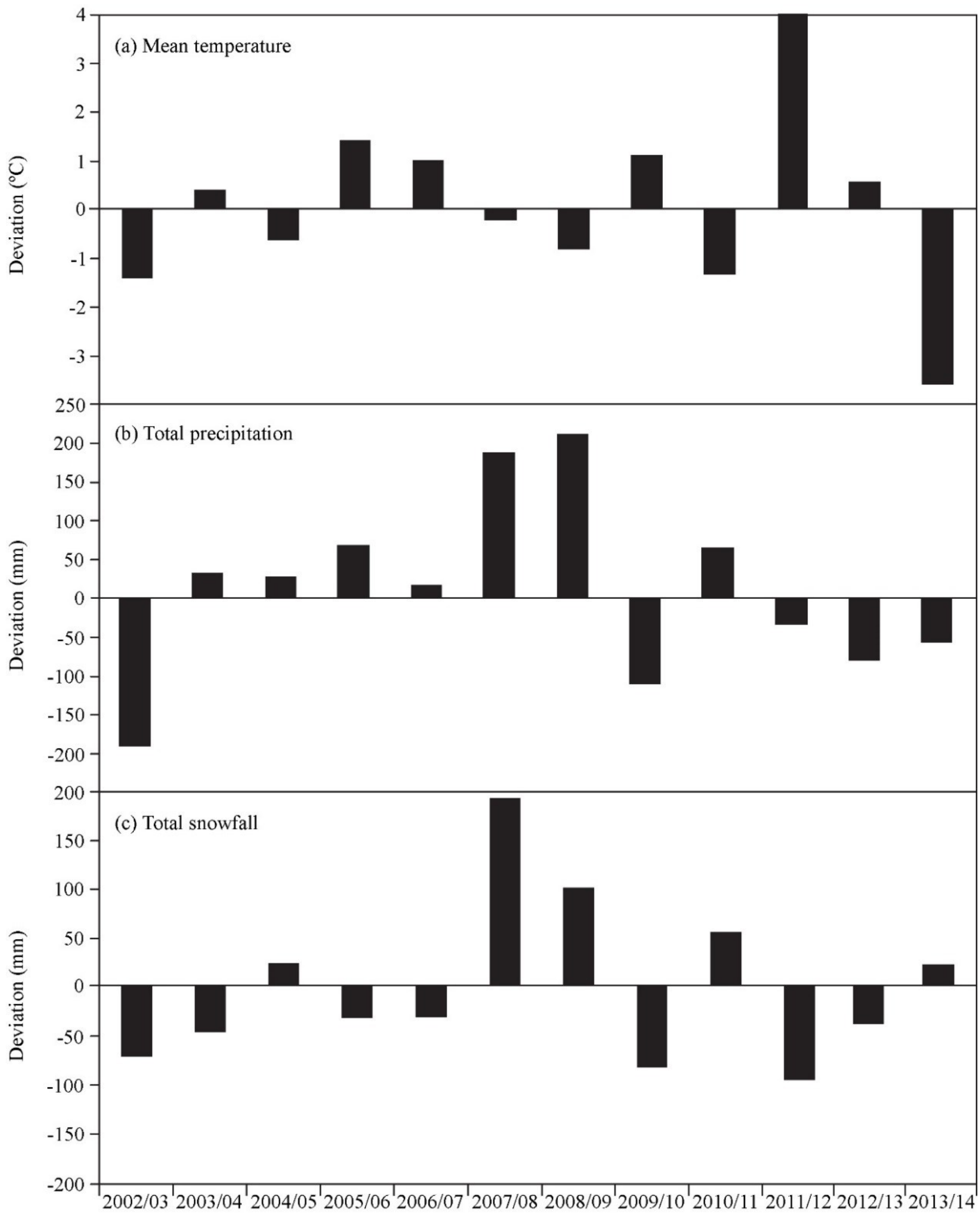

Figure 3. Deviations from the long term mean (1935 to 2014) for (**a**) mean winter temperature, (**b**) total winter precipitation and (**c**) total snowfall using the last twelve years of observed data from a weather station at Delhi, Ontario.

For 2009/2010, many strong oscillations occurred, including an El Niño event, positive PNA phase, and negative EPO, NAO and AO phases. Based on the general outcome predictions, there was a conflict as to how the local climate would be expected to respond. All phases of these oscillations tend towards lower amounts of precipitation in the Great Lakes region. Discrepancies arise in the expected winter temperature response as a positive PNA, and negative NAO and AO phases dominating the area would tend towards cooler temperatures, while the occurrence of the negative EPO phase and El Niño event would have brought warmer temperatures. During 2009/2010, drier conditions were evident, as both precipitation and snowfall were lower than normal (−110 mm and −79 mm respectively). The seasonal temperatures were warmer than normal (+ 1.1 °C), suggesting that the El Niño event or the negative EPO phase, or combination of both, was likely the stronger influence in the region that season. Seager *et al.* [62] determined that the strong El Niño event pushed the storm track further south, making warmer and drier conditions prevalent in the region. Without this strong ENSO event, the negative NAO would have produced colder temperatures.

The following year (2010/2011) had a strong La Niña event and a strong negative PDO phase, which should produce warmer and wetter conditions. A strong negative NAO phase was also present which can cool and dry the region. Temperatures for that season were below normal (−1.3 °C) with an observed increase in precipitation and snowfall (+63 mm and +57 mm respectively), producing similar colder and wetter conditions as observed in 2007/2008. In this year, perhaps the NAO had a stronger influence over the seasonal temperature than the La Niña and PDO events.

In 2011/2012, strong negative phases of the PNA, PDO and EPO were present, along with positive phases of both the NAO and AO, and a strong La Niña event. The overall pattern prohibited movement of Arctic air mass into the mid-latitudes and enhanced southerly flow and warm advection from the Gulf of Mexico into the Great Lakes region. Similar observations were made by Bai *et al.* [19] for this region. This generated record warmer and wetter seasonal values, such as 4 °C above the mean seasonal temperature in winter. In March 2012, an extreme warm event occurred in central and eastern North America for a majority of the month, which contributed to the above normal mean winter temperatures. Tropical heating anomalies over the Indian Ocean and western Pacific, due to an exceptionally strong Madden-Julian Oscillation (an oscillation partly linked to ENSO), contributed to the flow anomalies that were the cause for the extreme warm temperatures [63]. According to both the Delhi climate station and temperature records at our site, temperatures began to climb on March 11th and lasted fifteen consecutive days, peaking at 27 °C and 25 °C above the monthly normal at Delhi and our site, respectively. There was less winter precipitation (−34 mm), and less than normal total snowfall (−11 mm) as the majority of it fell as rainfall due to the warmer winter temperatures. This is in contrast to what was expected based on the combination of strong oscillations for the region.

In 2012/2013, only a strong negative phase of the AO was present, which typically allows colder, dry Arctic air into the region. Winter temperatures were slightly warmer than the mean (+0.5 °C), although much cooler than the previous winter. Both precipitation and snowfall were below the mean, −80 mm and −42 mm respectively. Finally in 2013/2014, strong positive phases of the NAO, AO and EPO were present. Both the NAO and AO typically bring in warmer and wetter conditions; however, the EPO is generally associated with cooler conditions. Mean winter temperature was considerably below the normal (−3.5 °C), with less precipitation (−58 mm) but more total snowfall (+19 mm). During this winter, cold temperatures were observed across much of North America due to anomalous meridional upper air flow, also referred to as a polar vortex [64].

Our analysis suggests that discrepancies between the predictions and outcomes are related to abrupt changes in climate patterns or one pattern becoming more dominant over another. Additionally, the regional climate of the Great Lakes can overshadow the influence of low frequency oscillations in some years on the local climate (such as thermal moderation and lake effect snow), making the climate complex and adding a large amount of uncertainty [20].

4.3. Impacts of Teleconnections on Carbon Fluxes

We evaluated the impact of low frequency climate oscillations on GEP, Re and NEP using observed flux data from 2003 to 2014. With significant correlations occurring mostly during the winter months against the different indices, we surmised that low frequency climate oscillations signals would have an impact on carbon fluxes through changes in weather variables. Although the forest was thinned in the winter of 2012, the thinning did not significantly impact the response of carbon fluxes as post-thinning fluxes were within the range of interannual variability [57]. Mean annual post-thinning GEP over the 2003 to 2014 period was 1518 ± 78 $gC \cdot m^{-2} \cdot year^{-1}$ as compared to pre-thinning GEP of 1384 ± 121 $gC \cdot m^{-2} \cdot year^{-1}$. Over the same period, mean post-thinning NEP was 185 ± 75 $gC \cdot m^{-2} \cdot year^{-1}$ as compared to post-thinning NEP of 180 ± 70 $gC \cdot m^{-2} \cdot year^{-1}$, indicating that mean annual pre-thinning NEP was not significantly different than post-thinning NEP ($p = 0.93$). Only post-thinning mean annual Re (1322 ± 54 $gC \cdot m^{-2} \cdot year^{-1}$) was higher than pre-thinning Re (1195 ± 101 $gC \cdot m^{-2} \cdot year^{-1}$). Detailed analysis of thinning impacts on carbon fluxes at this forest site has been reported by Trant [57].

Although the time period for this analysis is rather short in terms of climate variability (only twelve years of observed flux data as compared to the climate oscillations analysis from 1950 to 2014), these carbon flux data are among the rare long-term flux datasets available in global Fluxnet. Carbon fluxes are predominantly influenced by temperature and precipitation at a forest site, including ours [56–60,65]. Table 2 presents seasonal and annual temperature and precipitation correlations against GEP, Re, and NEP. In this analysis, a correlation with winter GEP was not included as little or no photosynthesis generally occurred during the winter season (December–March) in the region. Our analysis found that winter temperatures had significant positive correlations with winter Re and NEP values, while only GEP and Re had a significant positive response to spring temperatures. There were no significant correlations between the carbon fluxes and summer and autumn average temperatures. No significant correlations were found against seasonal total precipitation as well (Table 2). Annual NEP was correlated with annual total precipitation, although no significant relationships were found between annual NEP and total annual rainfall or snowfall (not shown). Winter NEP was inversely correlated with total snowfall. These results showed that that during the winter and spring seasons, carbon fluxes were sensitive to changes in the local temperature and precipitation. Similar results were reported by Zhang *et al.* [16].

Deviations from the twelve-year mean winter and spring carbon fluxes from 2003 to 2014 are shown in Figure 4. In winter and spring, with a decrease in precipitation and an increase in temperature, carbon fluxes generally became positive and increased in magnitude. Cold temperatures and lower precipitation resulted in the decrease in fluxes in spring of 2005, whereas the opposite occurred in 2010. For the 2011/2012 winter season, the large increase in seasonal temperature (Figure 3) had a strong effect on Re and NEP, strengthening the response of the forest to the climate forcing. These above normal winter temperatures increased Re (+34 g of C) and NEP (+39 g of C) over the twelve-year mean (Figure 4). The extreme warm event in March 2012, linked to strong climate oscillations, contributed the most to the seasonal increase in carbon fluxes. Cumulative Re measured by the eddy covariance system on top of the tower and daily mean temperature measured at 2 m above the surface in March for select years is shown in Figure 5. More Re occurred during March 2012 than opposing years (Figure 5a), even before the warm event began around 11 March (Figure 5b). At the onset on the extreme event, cumulative Re steadily increased with the rise in temperature, where this event alone released approximately 60 g of C from our forest. As temperatures returned to seasonal average, carbon re-release diminished.

Table 2. Correlation of gross ecosystem productivity (GEP), ecosystem respiration (Re) and net ecosystem productivity (NEP) against seasonal and annual mean temperature and precipitation from 2003 to 2014.

Period	GEP	Re	NEP
	Temperature		
Winter		0.63 *	0.67 *
Spring	0.86 **	0.88 **	0.25
Summer	−0.22	0.09	−0.45
Autumn	0.17	0.15	0.03
Annual	−0.21	0.04	−0.42
	Precipitation		
Winter		−0.21	−0.58
Spring	−0.16	−0.10	−0.12
Summer	0.23	0.33	−0.12
Autumn	−0.33	−0.30	−0.07
Annual	0.13	−0.27	0.62 *
	Snowfall		
Winter		−0.32	−0.66 *

* and ** indicates significance at the 95% and 99% confidence level.

As influences from these oscillations were strongest during the winter months, snow storage and melt were impacted. Increases in the snow pack, observed in 2007/2008 and 2008/2009 winters (Figure 3), most likely delayed the onset of growing season, but at the same time it increased soil moisture levels. In the 2011/2012 winter season, mild winters enhanced carbon uptake as the growing season length increased and more rainfall than snowfall. Additionally, enhanced winter precipitation recharged soil water reserves and reduced the likelihood of a later summer water stress [66].

Our analysis showed that only the EPO index had a significant negative relationship with spring values of GEP (Table 3). Re had a significant correlation with both EPO and PDO during the winter, while only a significant negative correlation with EPO was found in the spring. NEP only had a significant negative correlation with EPO during the winter. This significant relationship in the winter and spring with the EPO was likely the result of the 2011/2012 winter season, which had above normal winter temperatures and an extreme warm event in March, which coincided with a strong negative phase of the EPO that significantly increased these fluxes, as shown in Figures 4 and 5a. The significant correlation between the PDO and winter respiration may have been a result of respiration increase (decrease) in response to a decrease (increase) in the PDO phase. No connection between the PDO and local climate was found in this study. For the other seasons and on an annual basis, both the EPO and PDO generally showed a negative relationship with all three fluxes although not significant, where a negative (positive) phase would promote (undermine) these carbon fluxes. Mixed, weak relationships were found between the carbon fluxes and other indices.

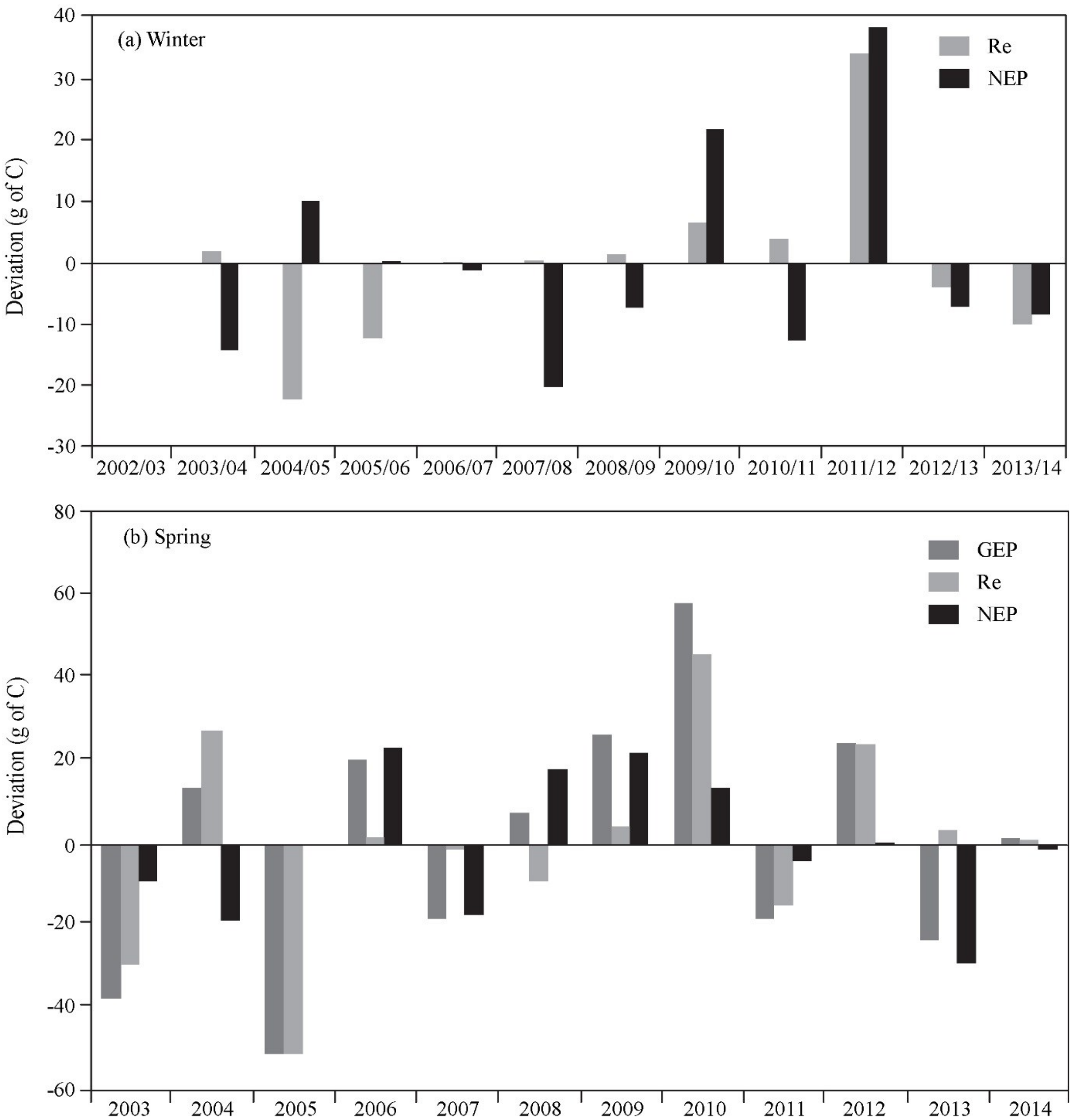

Figure 4. (**a**) Winter and (**b**) spring deviations from the mean gross ecosystem productivity (GEP), ecosystem respiration (Re) and net ecosystem productivity (NEP) over the period of 2003 to 2014. GEP for the winter season was not included as little or no photosynthesis occurred during the winter season in the region.

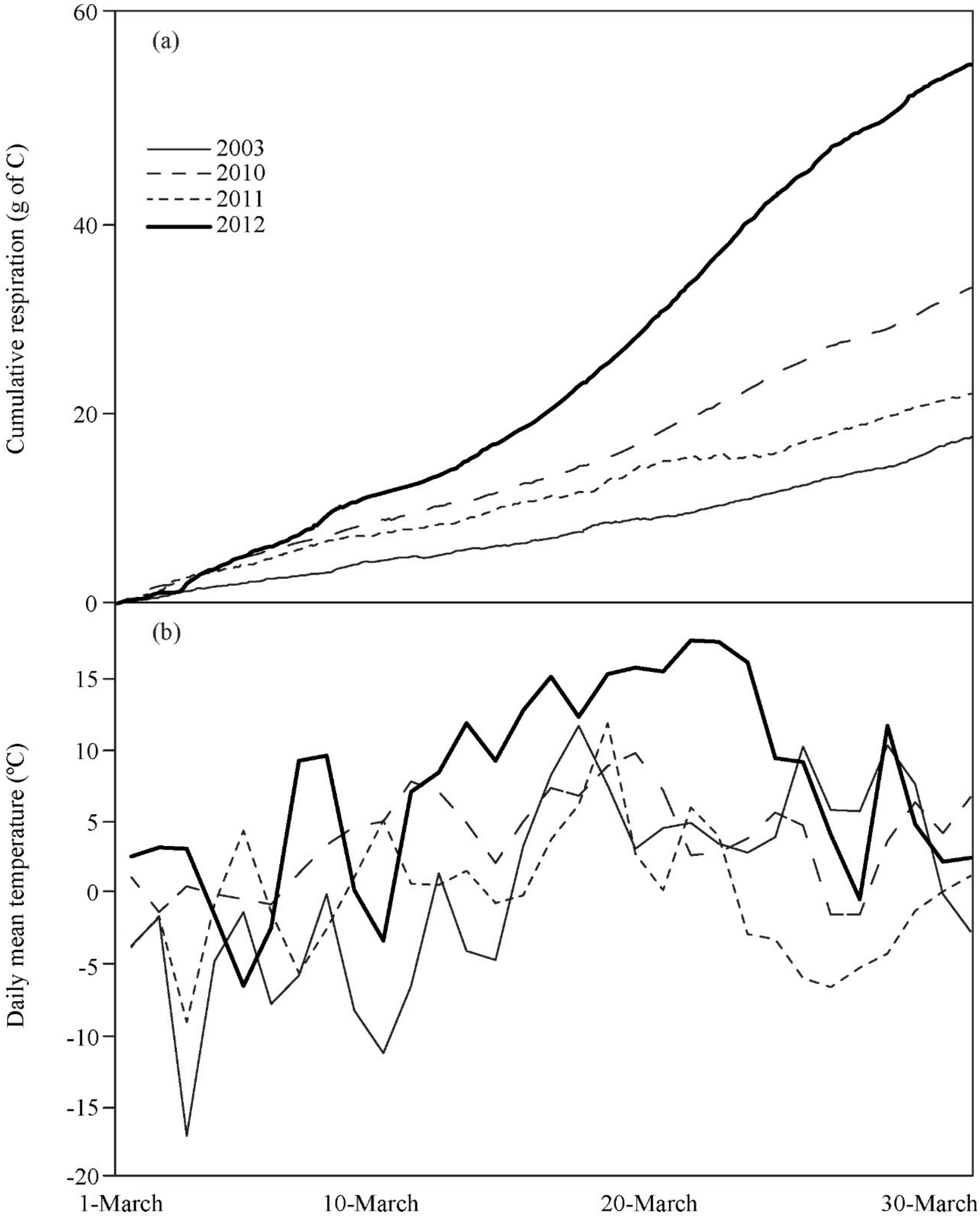

Figure 5. March **(a)** cumulative ecosystem respiration (Re) and **(b)** daily mean temperature measured at 2 m height in the forest shown for select years. In March 2012, an extreme warm event, linked to strong climate oscillations, began around 11 March and lasted fifteen consecutive days. This event contributed to the large increase in cumulative Re as compared to other years.

Teleconnection impacts on forest carbon exchange have been studied in other parts of North America. Grant *et al.* [67] examine the impact that changes in temperature and precipitation associated with large-scale weather events have on NEP from flux towers along a transcontinental transect of forest stands in Canada. Collectively, the results suggested that climate oscillations were reflected in NEP, although patterns may vary with climate zone, species and topography. Overall, warm episodes, which can be associated with ENSO/PDO events, were found to influence diurnal CO_2 exchange of temperate and boreal confiners but had little effect on boreal deciduous forests. Such warm events extended the period of net carbon uptake, increasing annual NEP at boreal coniferous and deciduous sites but had the opposite effect at a temperature coniferous site. However, these changes in NEP are more likely to occur within regions most affected by ENSO and PDO events; areas closer to the western coast of Canada. The only site in northern Ontario did not have any available data to evaluate effects of the ENSO and PDO events.

Hember and Lafleur [68] investigated the connections between the NAO and the North Pacific Oscillation (NPO), another teleconnection pattern that is correlated with the ENSO, with surface air temperature, precipitation and carbon fluxes. Using eddy covariance flux data spanning 1994–2006 from mid-latitude North American ecosystems, they found that in the spring, correlation in the southeast stations was positive between NAO and surface air temperature, while the NPO was positively (negatively) correlated with temperature (precipitation) in the northeast. Additionally, GEP and Re were positively correlated with NAO during the spring and summer at the south temperate sugar maple (*A. saccharum*) and tulip poplar (*Liriodendron tulipifera*) mixed forest located in Indiana, USA. Eastern stations were inversely correlated with NPO during spring, while positively correlated during the summer. In our study, the NAO only showed a significant positive correlation with winter temperatures, whereas the ENSO was only found to be significantly correlated with snowfall. No significant correlations were found between NAO, ENSO and the carbon fluxes; however, spring and summer fluxes were negatively correlated with NAO and mostly positively correlated with ENSO.

Zhang *et al.* [16] examined annual flux measurements from a deciduous forest in central Massachusetts, a coniferous forest in Maine, and a mixed hardwood deciduous forest in Indiana in USA. Their results indicated that climate oscillations influenced annual fluxes through their effects on the local surface climate. Minimum spring and summer temperatures, and fall temperatures were significantly inversely correlated with annual net ecosystem exchange (NEE = −NEP) and annual GEP. Winter precipitation had a significant positive correlation with annual NEE and GEP, while autumn precipitation had a significant negative correlation with annual NEE only. They also found that annual GEP was significantly related with fall Atlantic Multidecadal Oscillation (AMO), winter EPO, spring Multivariate ENSO Index (MEI) and PDO. Annual NEE was significantly correlated with fall AMO and PDO, while annual respiration responded to previous fall ENSO and PNA indices. Our findings showed strong correlations between winter and spring temperatures, and total snowfall against the winter and spring carbon fluxes. We also found similar relationships between winter temperature and NEP, and autumn temperature and GEP (not shown in Table 2). Also not shown in Table 2, and not found by Zhang *et al.* [16], was a significant positive correlation between spring precipitation and annual NEP. Against the indices, we only found that the EPO was correlated with winter and spring carbon fluxes, and the PDO related to winter Re. All other significant correlations were not found with the carbon fluxes from our site.

Table 3. Correlation of seasonal and annual gross ecosystem productivity (GEP), ecosystem respiration (Re) and net ecosystem productivity (NEP) against November to March mean climate oscillation index over the period of 2003 to 2014.

Period	PDO	PNA	ENSO	NAO	AO	EPO
			GEP			
Winter						
Spring	−0.35	0.08	0.16	−0.16	−0.21	−0.59 *
Summer	−0.14	0.06	0.20	−0.22	−0.18	0.13
Autumn	−0.31	−0.26	0.12	0.27	0.40	0.03
Annual	−0.35	−0.02	0.29	0.14	−0.09	−0.14
			Re			
Winter	−0.62 *	−0.18	0.36	0.25	0.17	−0.79 **
Spring	−0.24	0.05	0.02	−0.12	−0.27	−0.60 *
Summer	−0.05	0.37	−0.11	−0.07	−0.18	−0.16
Autumn	−0.19	−0.21	−0.12	0.56	0.47	−0.11
Annual	−0.26	0.16	−0.05	0.12	−0.02	−0.43
			NEP			
Winter	−0.11	0.30	−0.35	0.12	−0.07	−0.62 *
Spring	−0.26	−0.09	0.28	−0.13	−0.02	−0.18
Summer	−0.15	−0.32	0.44	−0.24	−0.06	0.38
Autumn	−0.15	−0.05	0.40	−0.55	−0.18	0.22
Annual	−0.23	−0.27	0.57	−0.41	−0.12	0.37

PDO: the Pacific Decadal Oscillation; PNA: the Pacific-North American; ENSO: El Niño-Southern Oscillation; NAO: North Atlantic Oscillation; AO: Arctic Oscillation; EPO: Eastern Pacific Oscillation. * and ** indicates significance at the 95% and 99% confidence level.

Although these studies in the literature and our study identified a relationship between local climate oscillations and carbon exchanges, differences in our findings and that of Grant *et al.* [67], Hember and Lafleur [68] and Zhang *et al.* [16] could be attributed to differences in geographic locations, hydrological conditions and different forest species. Our study found a significant link between climate oscillations and carbon fluxes, where local climate conditions were modified by the regional circulation in the Great Lakes region in eastern North America. Compared to other studies, a strong linkage was found between winter variables and winter and spring carbon fluxes such as Re and NEP. In particular, our examination of an extreme warm event which occurred in March 2012 on carbon fluxes was very interesting and demonstrated how severe these impacts may be if such warm events or heat stresses become more frequent and intense in future, as predicted by the future climate models [69].

5. Conclusions

Long term analyses of temperature and precipitation data in Southern Ontario, Canada showed that the local climate was strongly influenced by low frequency climate oscillations. Observed mean winter temperatures were positively correlated to the NAO and the AO, while negatively correlated with the EPO. Total winter precipitation was mainly influenced by the PNA and AO, while snowfall was found to have a strong relationship with the PNA and ENSO events. These impacts have been shown to influence Re and NEP during the winter, and GEP and Re during the spring season. The only direct connection between the carbon fluxes and the climate oscillations was a significant correlation between winter and spring fluxes and the EPO, the PDO, and winter respiration. The winter of 2011/2012 was unusual with strong negative phases of the PNA, PDO and EPO occurring along with positive phases of both the NAO and AO. These strong phases of climate oscillations generated record warm conditions, where average winter temperature was 4 °C above the mean seasonal temperature, causing a decrease in snowfall despite a slight increase in precipitation. These above normal winter temperatures had significant impact on winter carbon fluxes with increases observed in values of Re (+34 g of C) and NEP (+39 g of C) over the seasonal mean. March 2012 had an extreme warm event, linked to climate oscillations, which raised daily mean temperatures up to 25 °C above the monthly normal temperature and lasted fifteen consecutive days. This event alone released approximately 60 g of C from our site over the month of March. As large-scale modes of climate variability are important drivers to changes in climate extremes, changes to these modes will affect the intensity, frequency and spatial patterns of extreme climatic events, and can partially offset carbon sinks or even cause net losses in carbon stocks in plantation forests in our region. The knowledge gained from this research regarding the carbon sequestration in forest ecosystems and how low frequency climate oscillations will affect forest growth and their survival will help in developing polices for better management of forest ecosystems in Eastern Canada.

Acknowledgments

This study was funded by the Natural Sciences and Engineering Research Council (NSREC) Discovery and Strategic Grants and the Ontario Ministry of Environment and Climate Change (MOECC). Funding from the Canadian Foundation of Innovation (CFI) through New Opportunity and (T. A Black's group at University of British Columbia) for his contributions to flux and biometric data and Steve Williams (OMNRF) for his help and advice in field work at our site.

Author Contributions

Both Robin Thorne and M. Altaf Arain were involved in flux data measurements at the Turkey Point Flux Station. Robin Thorne performed data analysis and wrote first draft of manuscript. M. Altaf Arain contributed to write-up of subsequent drafts.

Conflicts of Interest

The authors declare no conflict of interest.

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