7.8   **Pacific Sea Surface Temperatures and their relation to Area Burned in Canada**

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1. INTRODUCTION

Forest fires are an integral ecological process in Canadian forests. Fires, in part, determine the structure, function and species composition of Canadian forests. Forest fires are strongly linked to weather and climate (Flannigan and Harrington 1988, Johnson 1992, Swetnam 1993). Despite the distance between the Pacific Ocean and Canadian forests a linkage may exist between the weather at both locations called a teleconnection. Teleconnection is a linkage between weather changes occurring in widely separated regions of the world (Greer 1996). One of the best known teleconnections is the Southern Oscillation in the equatorial Pacific Ocean or more commonly known as El Nino (ENSO). El Nino is characterized by a strong warming of sea surface temperatures (SST) in the eastern and central equatorial Pacific Ocean and is accompanied by a weakening of trade winds in this area.

Research has shown ENSO teleconnections with weather for North America. Horel and Wallace (1981) show that warm waters of the equatorial Pacific are well correlated with above normal geopotential heights over western Canada and below normal heights in the eastern U.S. Bunkers et al. (1996) study of the northern plains of the U.S. shows significant correlations between El Nino events and increased summer precipitation. The opposite correlation held for La Nina events. Shabbar et al. (1997) and Shabbar and Khandekar(1996) describe precipitation and temperature patterns across Canada associated with the southern oscillation and suggest that the significant correlations they find could be used as a long-range forecasting technique. Such forecasting of temperature and precipitation anomalies would be of importance to fire managers as these are two important factors affecting fuel moisture levels and the consequent levels of forest fire potential.

Studies of fire occurrence in association with El Nino and La Nina events have been carried out as well.Simard et al. (1985) divide the United States into 5

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regions and correlate fire occurrence and area burned per year in each of these regions with a relative El Nino intensity index using about 73 years of historical fire data. Their results imply that any relation between fire activity and El Nino occurrence in the continental U.S. will be regional in character. They found a significant correlation between El Nino occurrence and decreased fire activity in the southern states. No other statistically significant relationships could be found. Swetnam and Betancourt (1990) use fire scar, tree growth chronologies and fire statistics from Arizona and New Mexico and correlate these with the Southern Oscillation Index (SOI). The SOI is defined as the normalized difference in surface pressure between Tahiti, French Polynesia and Darwin, Australia. The SOI or its anomaly is often used as an index of the strength and duration of El Nino and La Nina events. Positive SOI values indicate a higher pressure in the Eastern Pacific and, as such, a La Nina event. Low SOI values indicate a lower pressure difference and an El Nino event. Swetnam and Betancourt found that in Arizona and New Mexico, large areas burn after La Nina events and smaller areas burn after El Nino events. This corresponded to drier and wetter springs in the American southwest associated with La Nina and El Nino events, respectively. Williams and Karoly (1999) show that fire weather is more extreme during El Nino seasons for central and southeast Australia. Brenner (1991) studied fire occurrence and area burned in Florida from 1950 to 1989. He found higher than average area burned in La Nina years and lower than average areas burned during El Nino years. It is interesting to note that in this study the highest correlations he found against area burned in Florida were with SST anomalies from the central Pacific.

The results of Brenner (1991) suggest there may be some value in looking at North Pacific SST for teleconnection not just with North American climate but with fire activity. A number of studies have shown a correlation between North Pacific SST and El Nino events (Reynolds and Rasmusson 1982, Trenberth 1990, Deser and Blackmon 1995). Studies of the North Pacific have shown SO like variability in SST pattern, which imply that a similar North Pacific Oscillation (NPO) exists (Zhang et al. 1997, Trenberth and Hurrell 1993, Tanimoto et al. 1993). A teleconnection known as the Pacific North American (PNA) teleconnection has in fact been identified between the Northern Pacific and North

America. During "high" index, the positive PNA has a negative anomaly in the north-central Pacific, a positive anomaly over western North America, and another negative anomaly over the southeastern U.S.A. This is indicative of an amplified meridional flow over western Canada (which is normally meridional). During "low" index flow is the opposite. A negative PNA index could also represent a weak meridional flow while a strong negative PNA index normally refers to zonal or in some cases "reverse meridional" flow, for example there is actual troughing over western Canada. The calculation of the PNA index is based on the flow at 500 mb whereas the calculation of NPO is based on SSTs. Walsh and Richman (1981) found a signature of this triple teleconnection when they used 31 years of North Pacific SST data and U.S. temperature data to show regional correlations. Their SST data correlated well with air temperature fluctuations over the far western states and the southeastern states but with opposite signs in the two regions. This work also suggested that such correlations could potentially be used for seasonal predictability in some areas. Johnson and Wowchuk (1993) found a signature of the PNA triple teleconnection during a study of 35 years of area burned data in the southern Canadian Rocky mountains. They found that during large fire years surface blocking high pressure systems in their study area were correlated with upper level troughs in the North Pacific and in Eastern North America. Skinner et al. (1999) found strong correlations between area burned in a number of regions in Canada and the presence of strong 500 mb level ridging. During extremely high years of area burned the PNA teleconnection pattern was evident with significant correlations between the 500 mb values at the 3 'triplet' locations.

Teleconnections from SSTs such as the Pacific North America pattern and those from the Southern Oscillation result from complex ocean-atmosphere forcing coupled with large scale atmospheric circulations. Climate modelling with coupled atmosphere/ocean models show that tropical flow patterns and consequent rainfall show little sensitivity to initial conditions of the atmosphere but are determined mainly by boundary conditions of SST in the Model (Shukla 1998) The details of these teleconnections are not as important as the fact that the relatively high temporal variability of weather parameters over land masses can be shown to be correlated with the more slowly varying oceans. Weather prediction limits based on the intrinsic variability in the atmosphere are thought to be on the order of 2 weeks. However, ocean variability occurs on a much slower time scale and as such teleconnections imply that seasonal climate prediction may be possible (Uppenbrink 1997). The use of such teleconnections as long-range forecasting tools has great appeal to all those involved in the fire business. Recent research has shown that the phase of the North Pacific Oscillation has a great influence on climate anomalies in North America during the SO (Gershunov et al. 1999). They found correlations between SO and Pacific SST and precipitation anomalies in North America to be much stronger during the high phase of the NPO. This has strong implications for longer term predictions of North America's weather and climate as the NPO varies with a 50-70 year time period (Minobe

1997). Being able to plan for the upcoming fire season's activity during the winter, based on current SST levels, could potentially allow fire management agencies greater efficiency in resourcing. Indeed, coupled atmosphere/ocean modelling of the strong El Nino in 1997/98 have shown very good results in predicting several months in advance the seasonal anomalies in North America for such important variables as precipitation anomalies (Kerr 1998); however, predicting fire activity is a difficult task. Forest fire occurrence and area burned tend have a strong dependence on shorter term, local weather, particularly drought and wind events, than they do on longer term conditions. Certainly an exceptionally dry or warm winter would seem to indicate a potential for much drier fuels for the upcoming fire season; however, on the small scale synoptic events such as showers or thunderstorms tend to dictate forest fire potential. However the correlations already found between area burned and the Southern oscillations and Pacific Ocean SSTs show there is hope that, with further analysis, these teleconnections could be used to qualitatively predict the fire severity potential of the upcoming fire season.

The objective of this paper is twofold. First, we explore the relationships between Pacific SSTs and area burned in Canada. Second, because of the inertia in the ocean system we wish to explore the potential of using SSTs to predict monthly or seasonal fire activity which, would be of great benefit to land managers.

2. DATA AND METHODS

The NPO has two phases that have a great influence on climate in North America; as a result, we divided our data by NPO for the analyses. The period 1953-76 was part of the low phase of the NPO while 1977-95 is part of the high phase of the NPO (Mantua et al., 1997).

The monthly mean Pacific SST data used are derived from the Comprehensive Ocean - Atmosphere Data Set (COADS) (Woodruff et al. 1987) from 20 degrees S to 58 degrees N for the period 1950 to 1995. The original 2 degree latitude by 2 degree longitude data have been transferred onto a 4 degree latitude by 8 degree longitude grid (Zhang et al., 1998) in order to reduce data gaps and to make a more reliable estimation of monthly means. Monthly SST anomalies for each NPO phase were computed for each grid point and used in this study. Monthly area burned data for May to September was obtained for 8 broad regions of Canada for 1953-1995. These regions include British Columbia, combined Yukon and Northwest Territories, Alberta, Saskatchewan, Manitoba, Western Ontario (West of Lake Nipigon), Eastern Ontario and Quebec. The May - September period encompasses most of the fire season in Canada. The natural logarithm of the area burned was used as the area burned data is not normally distributed. Monthly anomalies of the natural logarithm of the area burned data were calculated in the same way that the SST data was.

Monthly and seasonal area burned for each province was correlated with SST anomalies. In addition to using current time period for correlation we also used lags of up to 3 months for the monthly analysis and for the

seasonal area burned we used the SST data for January - April.

3. RESULTS AND DISCUSSION

Tables 1 and 2 show the best correlation between monthly area burned in each province and SST for the current month and up to a lag of 3 months(e.g., May's area burned correlated with February's SST) according to NPO phase. Tables 3 and 4 show the correlation between provincial seasonal area burned and SST according to the NPO phase. The tables also show the location of the maximum correlation. The correlations were mapped to see what kind of spatial pattern was evident. Figure 1 shows the correlations between monthly area burned in Eastern Ontario and SST for the current month and for the previous month (one month lag). From Figure 1 it is apparent that there is some spatial coherency in the correlation and that these are not random correlations and there are definite centers of correlation. Some of this spatial and temporal coherency in the SST correlation pattern is because of the autocorrelation of the SST data.

further. The correlations are very good considering all the factors that come into play for a complex variable like area burned. Factors such as multiple fire starts, fire control policies and priorities, fire management organizational efficiency, accessibility of fires, topography, nature and extent of the fuel, etc. all can influence area burned. Exploring the connection between fire weather severity and SSTs might lead to even better results as fire weather severity is not influenced by as many factors as area burned. Figures 2 and 3 show the relationship between the seasonal area burned in Eastern Ontario and the lagged (Jan.- Apr.) SST anomaly for the 1977-95 period with a time series and a scatter plot. The correlation is .64 (Table 4) which explains about 41% of the variation in the data.

These results compare well with other studies looking at provincial area burned as related to components of the Canadian Forest Fire Weather Index (FWI) System (Harrington et al. 1983) and meteorological variables (Flannigan and Harrington 1988). These two studies used data from the current month and from stations within each provincial area so it is not surprizing that their correlations are better than SST for western Canada but for Eastern Ontario and Quebec the SST correlations are as good or better as these other studies.

Province	No lag	lag
BC	**0.60** **48 N 118 W**	0.53 16 S 106 E
Yukon/NWT	**0.65** **28 N 170 E**	0.64 20 S 178 E
Alberta	-0.47 20 S 154 E	**-0.72** **36 N 142 W**
Sask.	**0.55** **32 N 178 E**	0.51 16 N 166 W
Man.	0.57 36 N 146 E	**0.61** **24 N 174 W**
W. Ont.	-0.67 12 N 150 W	**-0.70** **4 N 150 W**
E. Ont.	-0.62 20 N 150 W	**-0.70** **20 N 134 W**
Que.	0.65 28 N 150 W	**-0.72** **4 N 102 W**

Table 3. Maximum correlation between Pacific SSTs and seasonal provincial area burned 1953-76. The location of the maximum correlation is displayed as well. Bold values indicate maximum correlation for each region.

Province	No lag	lag
BC	**-0.64** **56 N 134 W**	-0.52 20 N 102 W
Yukon/NWT	**-0.77** **20 S 162 E**	0.68 20 N 122 E
Alberta	**0.56** **24 N 142 W**	0.55 0 N 162 E
Sask.	**0.58** **20 N 146 E**	-0.55 12 S 162 E
Man.	**0.73** **16 N 146 E**	0.60 12 N 130 E
W. Ont.	**0.62** **20 N 138 E**	0.59 4 N 118 W
E. Ont.	**0.64** **20 N 94 W**	0.64 4 S 146 E
Que.	**0.68** **8 S 154 E**	0.62 20 S 106 E

Table 4. Maximum correlation between Pacific SSTs and seasonal provincial area burned 1977-95. The location of the maximum correlation is displayed as well. Bold values indicate maximum correlation for each region.

The correlations are significant (above 99% level) in all cases and give support to the possibility that SST could be used in a predictive fashion especially in the seasonal forecast. These results are from a dependent data set and from relatively small sample sizes but the prediction capabilities of using SSTs should be explored

The NPO seems to be playing a major role in the relationship between SST and area burned. The high phase of the NPO (present phase) is characterized by anomalously deep Aluetian low, cold western and central north pacific, warm eastern Pacific coastal waters.

Province	No lag	1 month	2 months	3 months
BC	**0.39** **40 N 134 W**	0.30 28 N 162 E	0.29 4 S 158 W	0.31 52 N 174 W
Yukon/ NWT	-0.35 48 N 178 E	**0.45** **24 N 170 E**	-0.33 48 N 178 E	0.35 28 N 178 E
Alberta	**0.34** **36 N 170 E**	-0.31 16 N 174 W	0.31 28 N 162 E	-0.30 36 N 134 W
Sask.	**0.33** **40 N 170 E**	0.27 16 S 146 E	0.30 8 N 174 W	0.31 16 S 146 E
Man.	0.27 36 N 146 E	**0.30** **52 N 166 W**	0.29 8 N 178 E	-0.29 40 N 142 W
W. Ont.	**-0.52** **16 N 158 W**	-0.42 16 N 158 W	-0.48 4 N 158 W	-0.47 8 N 158 W
E. Ont.	-0.42 20 N 158 W	**-0.48** **20 N 150 W**	-0.39 20 N 134 W	-0.42 20 N 134 W
Que.	0.35 20 S 174 E	0.32 32 N 150 W	**0.47** **32 N 118 W**	-0.36 12 N 86 W

Table 1. Maximum correlation between Pacific SSTs and monthly provincial area burned 1953-76. The location of the maximum correlation is displayed as well. Bold values indicate maximum correlation for each region.

Province	No lag	1 month	2 months	3 months
BC	**-0.39** **52 N 166 W**	-0.31 52 N 166 W	-0.33 24 N 122 E	-0.26 56 N 134 W
Yukon/NWT	-0.40 20 S 162 E	0.41 48 N 142 W	0.41 48 N 150 W	**0.47** **48 N 150 W**
Alberta	0.34 32 N 162 E	0.32 0 N 154 E	**0.37** **52 N 174 W**	0.27 16 N 94 W
Sask.	-0.31 4 N 154 E	**0.38** **24 N 142 W**	0.34 12 N 170 E	0.30 8 N 122 E
Man.	**0.44** **12 N 154 E**	0.42 20 N 146 E	0.34 20 N 146 E	0.37 16 N 170 E
W. Ont.	**0.38** **8 N 114 E**	0.33 12 S 94 W	0.32 16 S 110 W	0.29 4 S 86 W
E. Ont.	0.38 28 N 138 E	**0.38** **4 S 154 E**	0.29 4 S 154 E	0.24 4 N 162 E
Que.	**0.41** **8 S 154 E**	0.29 4 S 114 E	0.37 8 S 154 E	0.33 16 S 166 W

Table 2. Maximum correlation between Pacific SSTs and monthly provincial area burned 1977-95. The location of the maximum correlation is displayed as well. Bold values indicate maximum correlation for each region.
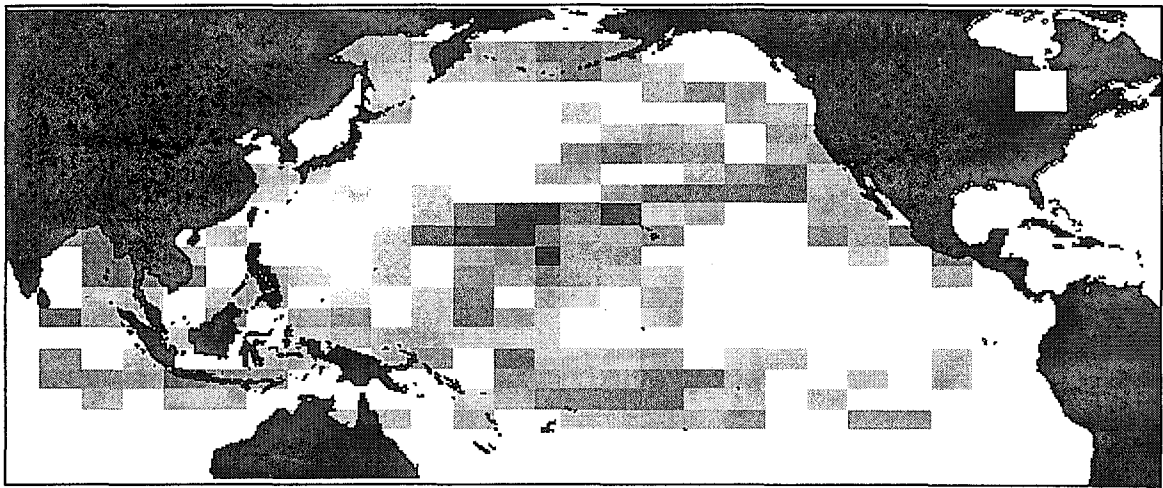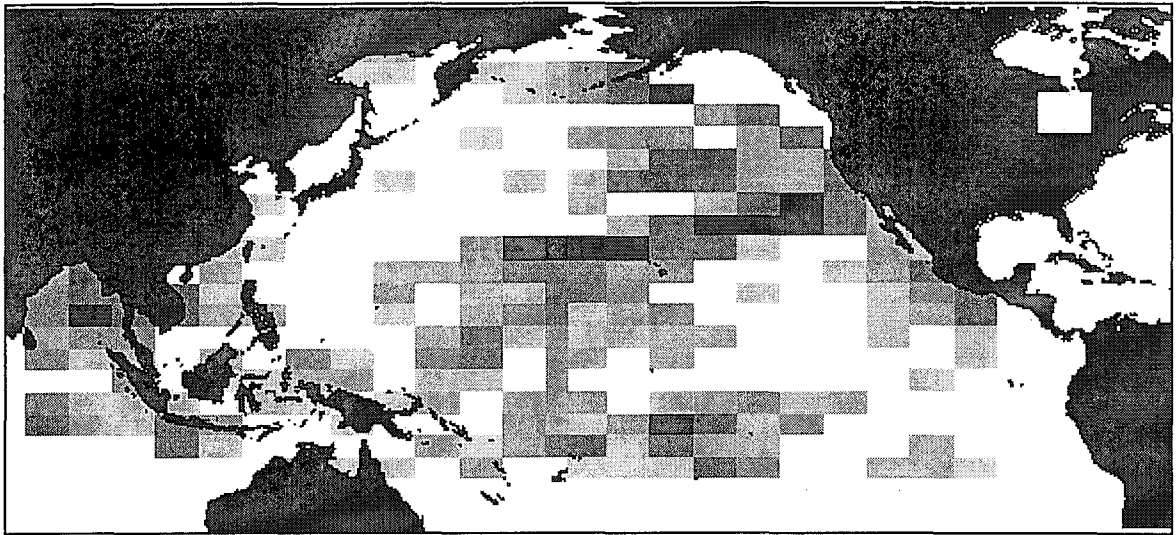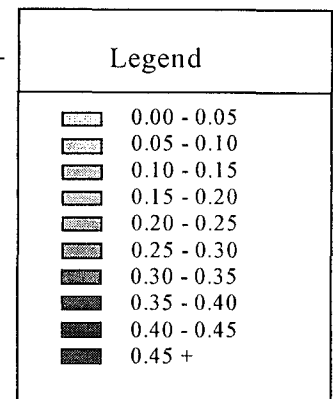
Figure 1. Absolute value of the correlation between normalized monthly Pacific SST anomalies and normalized monthly area burned in Eastern Ontario 1953-76. Top figure is for no lag and the bottom figure is for a one month lag. The white cell just south of Hudson's Bay shows the approximate location of Eastern Ontario.

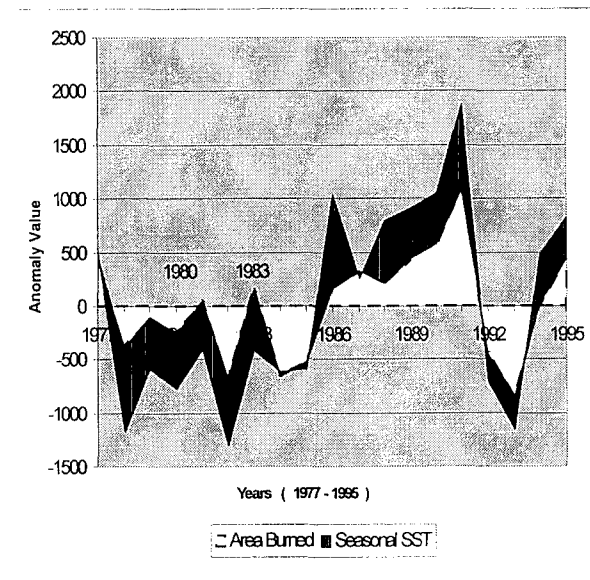| Legend	
	0.00 - 0.05
	0.05 - 0.10
	0.10 - 0.15
	0.15 - 0.20
	0.20 - 0.25
	0.25 - 0.30
	0.30 - 0.35
	0.35 - 0.40
	0.40 - 0.45
	0.45 +

Figure 2. Normalized seasonal area burned in Eastern Ontario and lagged (Jan.-April) SST anomaly for 1977-95.
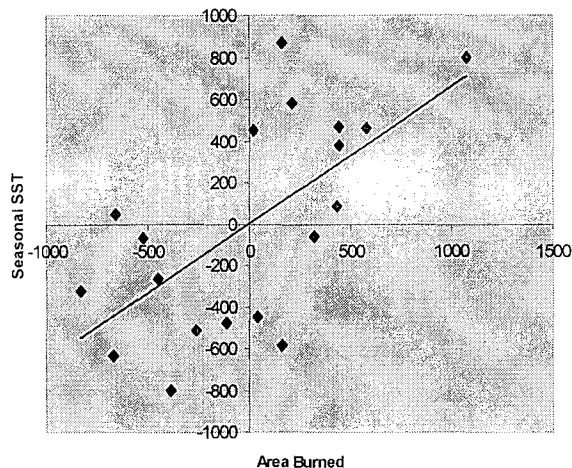

Figure 3. Normalized SST anomaly (Jan. - April) versus normalized seasonal area burned for Eastern Ontario 1977-95.

Reversed climatic conditions characterize the low NPO phase. These conditions in the Pacific influence atmospheric circulation in the low levels and the upper levels of the atmosphere (500 mb). We expect that there is a relationship between the SST in regions of the Pacific and the location of ridges and troughs in the upper flow over Canada similar to the PNA teleconnection. The warm dry weather associated with upper ridges are conducive to fire activity whereas the cool and often wet conditions associated with upper troughs are not conducive to fire

activity.

Results from this study are promising in terms of using SSTs to predict fire activity. If land managers had guidance in terms of the potential fire activity for the upcoming month or season for their jurisdiction it would allow them to prepare accordingly. These forecasts will not be without error but should be better than using climatology especially now as it appears our climate is changing.

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