Ecological Modelling 221 (2010) 122–129

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Correlations between forest fires in British Columbia, Canada, and sea surface temperature of the Pacific Ocean

Yonghe Wang[a,*], Mike Flannigan[b], Kerry Anderson[a]

[a] Canadian Forest Service, Northern Forestry Centre, 5320 – 122 Street, Edmonton, AB, Canada T6H 3S5
[b] Canadian Forest Service, Great Lakes Forestry Centre, P.O. Box 490, 1219 Queen Street East, Sault Ste. Marie, Ontario, Canada P6A 2E5

ARTICLE INFO

Article history:
Available online 21 January 2009

Keywords:
Lightning-caused forest fires
Human-caused forest fires
Sea surface temperature anomaly
Cross-correlation
Spectral analysis

ABSTRACT

Correlations and cross-correlations between forest fires in the province of British Columbia, Canada, and sea surface temperatures in the Pacific Ocean were evaluated. British Columbia has a long Pacific Ocean coastline; given that there may be teleconnections between the province's forest fires and climate variability over the ocean, significant correlations may exist between forest fires and the sea surface temperature of the Pacific Ocean. Fire occurrences and areas burned through lightning-caused and human-caused fires were analyzed against individual $1^\circ \times 1^\circ$ grid cells of anomalies in the sea surface temperature to determine correlations for the period 1950–2006. Significant correlations ($p < 0.05$) for vast areas of the ocean were found between occurrences of lightning-caused fires and sea surface temperature anomalies for time lags of 1 and 2 years, whereas significant correlations between occurrences of human-caused fires and sea surface temperature anomalies occurred extensively for many time lags. To support the results of this approach, correlations between fire data and the Niño 3.4, Pacific Decadal Oscillation, and Arctic Oscillation indices were tested for the same period. Significant correlations were found between fire occurrences and these indices at certain time lags. Overall, fire occurrence appeared to be more extensively correlated with sea surface temperature anomalies than was area burned. These results support the hypothesis that teleconnections exist between fire activity in British Columbia and sea surface temperatures in the Pacific Ocean, and the correlations suggest that linear regression models or other regression techniques may be appropriate for predicting fire severity from the sea surface temperatures of one or more previous years.

1. Introduction

Adjacent to the Pacific Ocean, British Columbia (BC) is Canada's westernmost province (Fig. 1). It has an area of 94×10^6 ha, of which 49.9×10^6 ha is considered productive forest land. In total, an area of 80×10^6 ha in the province requires protection from wildfire. On average, approximately 2000 forest fires occur each year in BC, burning approximately 27×10^3 ha. During the fire season (from March to October), the provincial government carries out various fire-protection and fire-suppression activities to mitigate the associated risks and potential damage (BC Ministry of Forests and Range).

Despite the distance between the Pacific Ocean and BC's forests, connections may exist between the weather at the two locations. Such connections between weather and other climatic phenomena occurring in widely separated regions of the world are called teleconnections (Greer, 1996). One of the best-known sources of teleconnections is the Southern Oscillation in the equatorial Pacific Ocean, more commonly known as El Niño. It is characterized by a strong warming of the sea surface temperature (SST) in the eastern and central equatorial Pacific Ocean, which is accompanied by a weakening of the trade winds in this area. In contrast, La Niña is characterized by unusually cold SST in the eastern and central equatorial Pacific. Research has revealed that El Niño teleconnections affect the weather of North America (Horel and Wallace, 1981; Bunkers et al., 1996; Shabbar et al., 1997).

Forest fires are strongly influenced by weather and climate (Flannigan and Harrington, 1988; Johnson, 1992; Swetnam, 1993). Studies of the occurrence of fire in association with El Niño and La Niña events have suggested a significant correlation between El Niño occurrence and lower fire activity in the southern part of the United States (Simard et al., 1985). In addition, Swetnam and Betancourt (1990) found that large areas of Arizona and New Mexico have burned after La Niña events, whereas smaller areas in these states have burned after El Niño events. Williams and Karoly (1999) showed that fire weather is more extreme during El Niño seasons for central and southeast Australia. Skinner et al. (1999) found strong correlations between area burned in a number of regions of

* Corresponding author. Tel.: +1 780 435 7237; fax: +1 780 435 7359.
E-mail address: ywang@nrcan.gc.ca (Y. Wang).

0304-3800/$ – see front matter. Crown Copyright © 2009 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2008.12.007

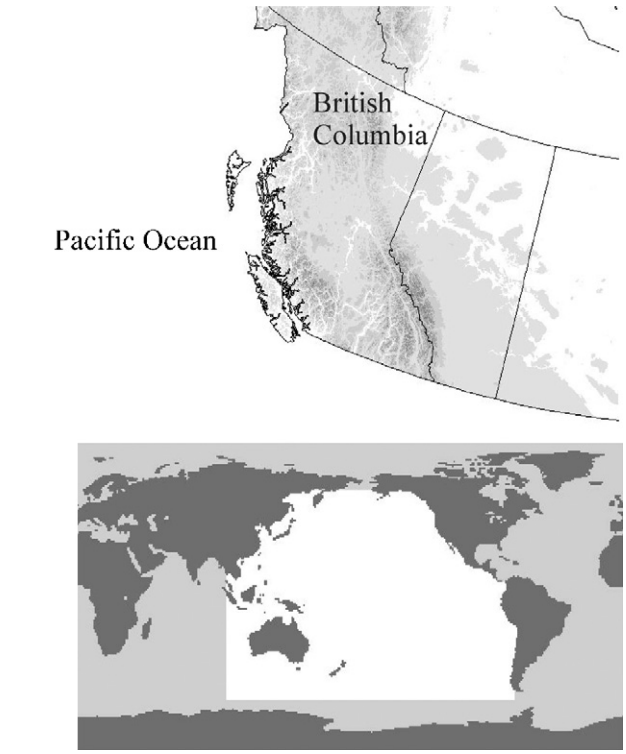

Fig. 1. The Canadian Province of British Columbia (top), and the Pacific Ocean study region, bounded by 60°N, 60°S, 102°E, and 72° W (bottom).

Canada and the presence of strong 500-mb level ridging, an atmospheric feature related to SSTs. In Florida, Brenner (1991) found higher-than-average area burned in La Niña years and lower-than-average area burned during El Niño years; the strongest correlations involved SST anomalies in the central Pacific Ocean. These findings, along with studies that have shown a correlation between North Pacific SSTs and El Niño events (Reynolds and Rasmusson, 1982; Trenberth, 1990; Deser and Blackmon, 1995) suggest that there may be some value in examining Pacific SSTs for teleconnections with fire activity.

The aim of this study was to determine if teleconnections exist between BC forest fires and climatic phenomena such as El Niño by calculating correlations between fire activity and Pacific SSTs. We hypothesize that BC forest fires are influenced by the Pacific SST variability such that teleconnections exist between the fire and SST. Simple correlations and cross-correlations with lag effects were used to compute correlation coefficients and to test their statistical significance. In addition, the periodic properties of fire variables were compared, and correlations between fire and other climatic indices were examined to determine support for the results. Significant correlations were regarded as evidence that fire activity in BC is influenced by Pacific SSTs and that certain teleconnections exist between BC fires and SSTs. Such knowledge can be used to build mathematical models predicting the severity of fire activity in the province, based on variations in the climate system over the Pacific Ocean. Such models would greatly assist fire management decisions and operations within the province.

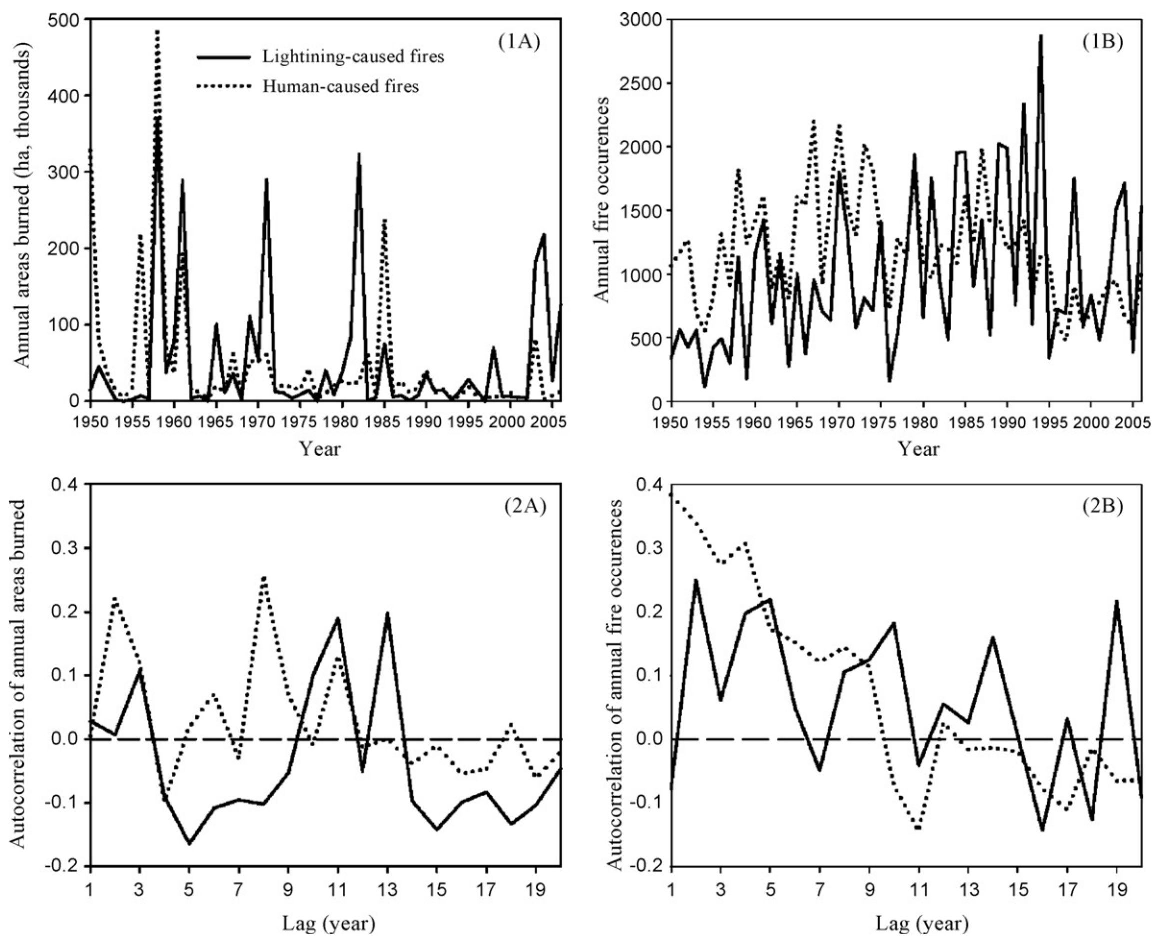

Fig. 2. Annual area burned (plot 1A) and annual fire occurrence (plot 1B) for lightning- and human-caused fires in British Columbia over the period 1950–2006. Autocorrelation coefficients for lags of one to 20 years were determined for area burned (plot 2A) and fire occurrence (plot 2B). Periodgrams for periods of three to 10 years were also determined for annual area burned (plot 3A) and fire occurrence (plot 3B). The *y*-axes of plots 3A and 3B have different scales and not directly comparable.

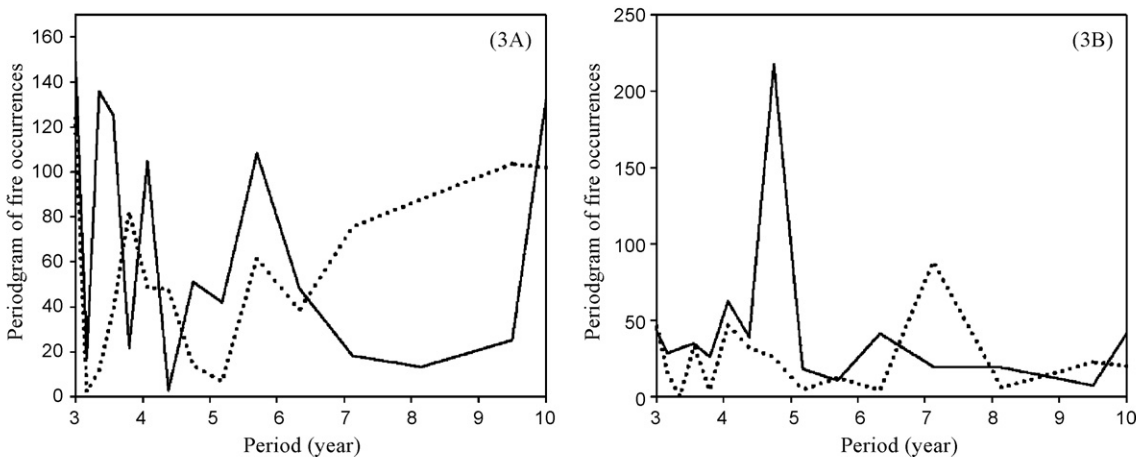

Fig. 2. (*Continued*).

2. Data and analysis

BC forest fire data for the period 1950–2006 were used in this study. We collected data on fire occurrence and area burned for both human-caused and lightning-caused fires (i.e., a total of four fire variables) from the annual reports for each provincial district. These values were combined to produce annual provincial values for analysis.

The four fire variables used in this study can be represented as time series (Fig. 2, plots 1A and 1B). We checked for possible autocorrelations in these time series using the PROC ARIMA procedure in SAS/ETS software (SAS Institute Inc., 2004), which yielded the coefficients of autocorrelation shown in plots 2A and 2B of Fig. 2. There were no significant correlations for any of the time lags, which suggest no autocorrelation for the period 1950–2006. Because the four fire variables represent time series, they were also assessed for potential periodicity. We used the PROC SPECTRA procedure in SAS/ETS to conduct spectral analysis for the fire data. According to the resulting periodgrams (Fig. 2, plots 3A and 3B), the periodic properties of fire occurrence differed from those of area burned; even within each of these two variables, the two sets of data (i.e., for human- and lightning-caused fires) had different periodic properties.

SST is an important indicator of the state of the earth's climate. Using both in situ and satellite data from 1982 to the present, the National Oceanic and Atmospheric Administration (NOAA) in the United States produces a monthly analysis of optimum interpolated SST with spatial resolution of $1^{\circ} \times 1^{\circ}$. Interpolated SST, represented by a grid of 180 rows and 360 columns covering the globe, has been widely used for monitoring and forecasting both weather and climate (Reynolds et al., 2002; Smith and Reynolds, 2004). Monthly SST data were obtained from the NOAA. Another source of global monthly SST data was the Global Ocean Surface Temperature Atlas (GOSTA), jointly published by the Meteorological Office of the United Kingdom and the Massachusetts Institute of Technology (Bottomley et al., 1990; Reynolds and Smith, 1995). The grid data set in GOSTA also has a spatial resolution of $1^{\circ} \times 1^{\circ}$, but it covers only the period from 1950 to 1994. The two SST data sets cover the globe, but for the purposes of this study, the analysis was limited to values in the study region (i.e., the Pacific Ocean) (Fig. 1).

The common period for the two SST data sets was 1982–1994. If the differences between the two sources are negligible, the two sets can be grouped to create a single data set spanning from 1950 to 2006, either by combining the GOSTA data from inception (in 1950) to 1981 with NOAA data from inception (in 1982) to 2006 or by combining the complete GOSTA data set (1950–1994) with NOAA data for 1995–2006. Differences in annual mean temperatures between the two SST sources were checked, grid cell by grid cell, for the common period 1982–1994, but the differences were negligible: 93% of the cell-wise differences were within 0.5 °C (Fig. 3). Therefore, we combined the GOSTA data for 1950–1981 and the NOAA data from inception to 2006 as our SST data set for the study period 1950–2006.

From the monthly data, annual mean SST (SSTY) was derived as follows for each year for each grid cell:

$$\overline{\mathrm{SSTY}_i} = \frac{\sum_{j=1}^{12} \mathrm{SST}_{ij}}{12} \tag{1}$$

where i denotes years from 1950 to 2006; $j = 1–12$, representing months from January to December; and SST_{ij} denotes the SST value

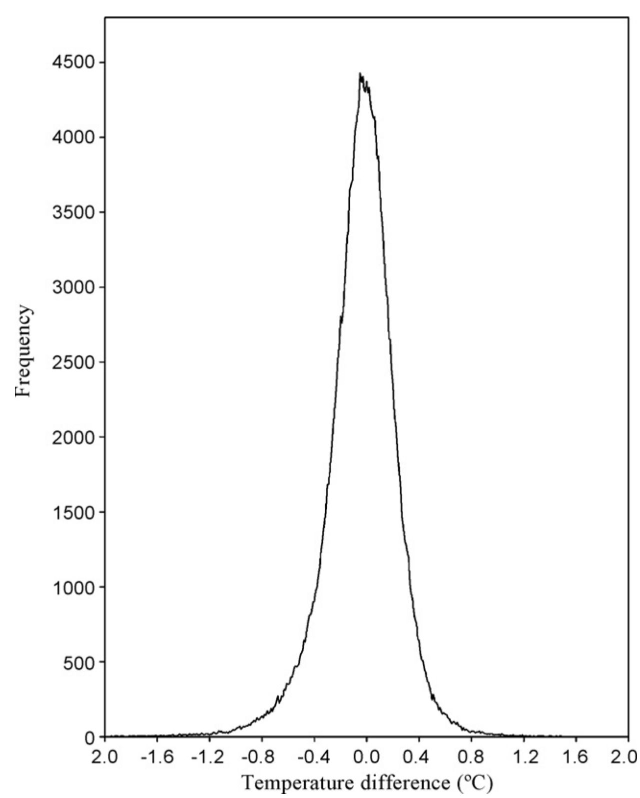

Fig. 3. Histogram for difference in sea surface temperature between data obtained from the National Oceanic and Atmospheric Administration and data taken from the Global Ocean Surface Temperature Atlas for all grid cells in the study region for 1982–1994 (the period of overlap for the two data sets).

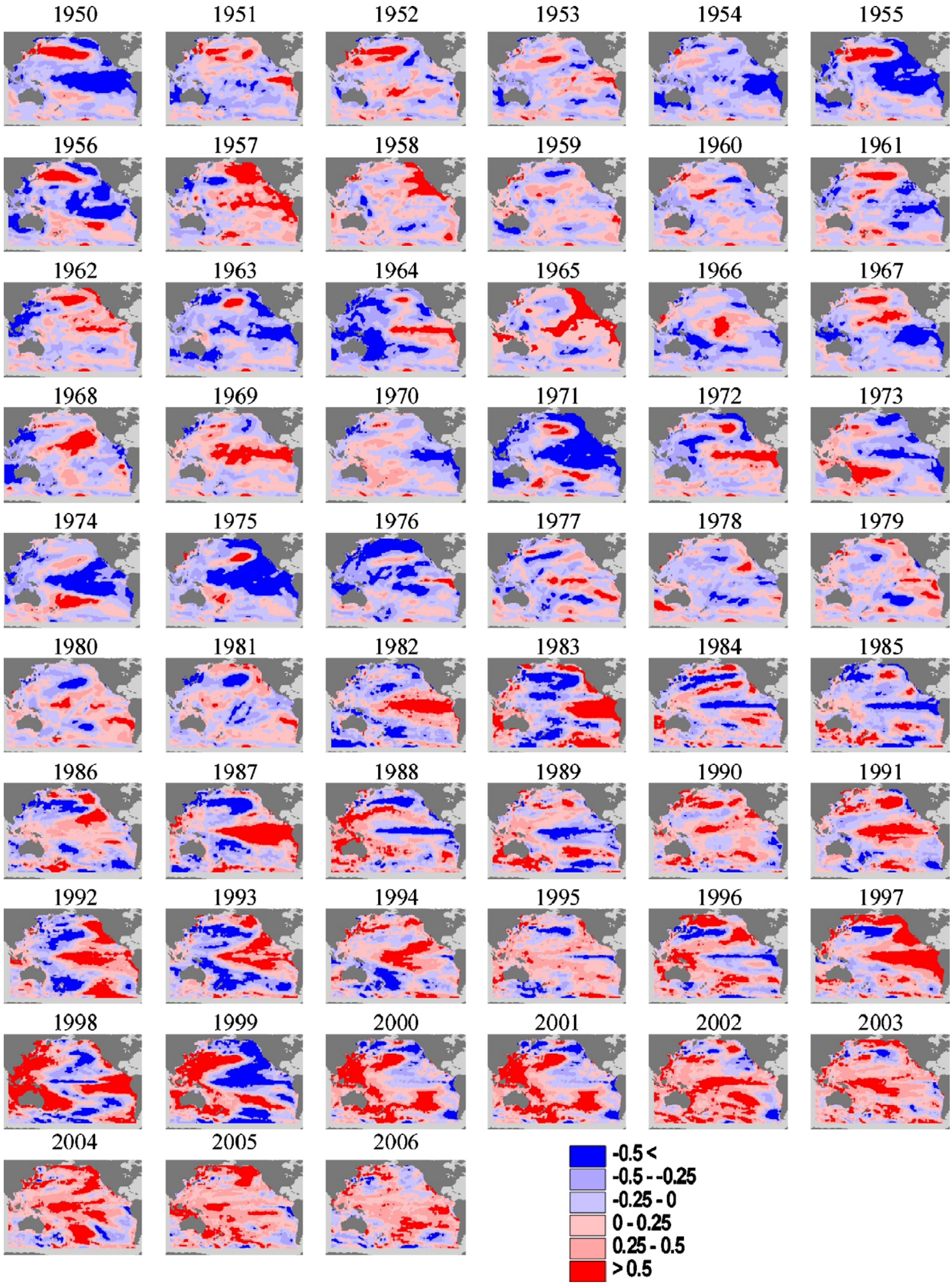

Fig. 4. Annual mean anomalies (°C) in sea surface temperature for the study region, based on the combined data set for 1950–2006, derived from National Oceanic and Atmospheric Administration data and the Global Ocean Surface Temperature Atlas.

for the ith year and the jth month. In addition, annual mean SST anomalies were determined by first calculating the 12 monthly mean SSTs (SSTM) at each grid cell as follows:

$$\overline{\mathrm{SSTM}}_j = \frac{\sum_{i=1950}^{2006} \mathrm{SST}_{ij}}{57} \tag{2}$$

where $j = 1–12$ representing the 12 months of the year. Monthly anomalies (ANO) were produced at each grid cell as follows:

$$\mathrm{ANO}_{ij} = \mathrm{SST}_{ij} - \overline{\mathrm{SSTM}}_j \tag{3}$$

where i signifies years from 1950 to 2006 and $j = 1–12$ for the 12 months of the year. Annual mean SST anomalies (ANOY) were then derived as follows (see Fig. 4):

$$\overline{\mathrm{ANOY}}_i = \frac{\sum_{j=1}^{12} \mathrm{ANO}_{ij}}{12} \tag{4}$$

Possible time-delayed effects of climate on fire were considered by calculating the correlations between SST anomalies and fire variables in the same year and cross-correlations between each year's fire data and anomalies in previous years. For example, for delay (lag) = 0 years, fire data and SST anomalies for the same time period were correlated. For lag = 1 year, fire data from 1951 to 2006 were cross-correlated with anomalies from 1950 to 2005, respectively, and so forth.

In addition to correlations determined with the Pacific SST data, we analyzed possible correlations between BC fire variables and three other commonly used indices. The first of these, the Niño 3.4 index, represents the SST anomaly averaged for the Pacific region from 5°N to 5°S and from 120°W to 170°W. It reflects the dominant mode of coupled atmosphere–ocean variability on interannual time scales, and it has been quantified in terms of a simple index (Trenberth, 1997; Trenberth and Stepaniak, 2001). The Pacific Decadal Oscillation (PDO) is a long-lived ENSO-like pattern of Pacific climate variability, and its climatic "fingerprints" are most visible in the North Pacific and North American sector (Zhang et al., 1997). The Arctic Oscillation (AO) is the dominant pattern of non-seasonal variation in sea level pressure north of 20°N, and it reflects circulation patterns in the Arctic region (Thompson and Wallace, 1998). The indices represent three distinctly different temporal scales of variability ranging from short-term scales of 2–7 years for Niño 3.4 index, to decadal scales for PDO, and even longer scales for AO. Balzter et al. (2005) found significant relations between AO and the annual area burned in the forests of central Siberia. The data sets for Niño 3.4, PDO, and AO cover the study period of 1950–2006. The cross-correlations described above were also carried out between the fire data and the Niño 3.4, PDO, and AO indices.

3. Results and discussion

We calculated correlations and cross-correlations (for 12 lag periods, i.e., from 1 to 12 years) between annual mean SST anomalies and BC fire data for all grid cells in the Pacific study region;

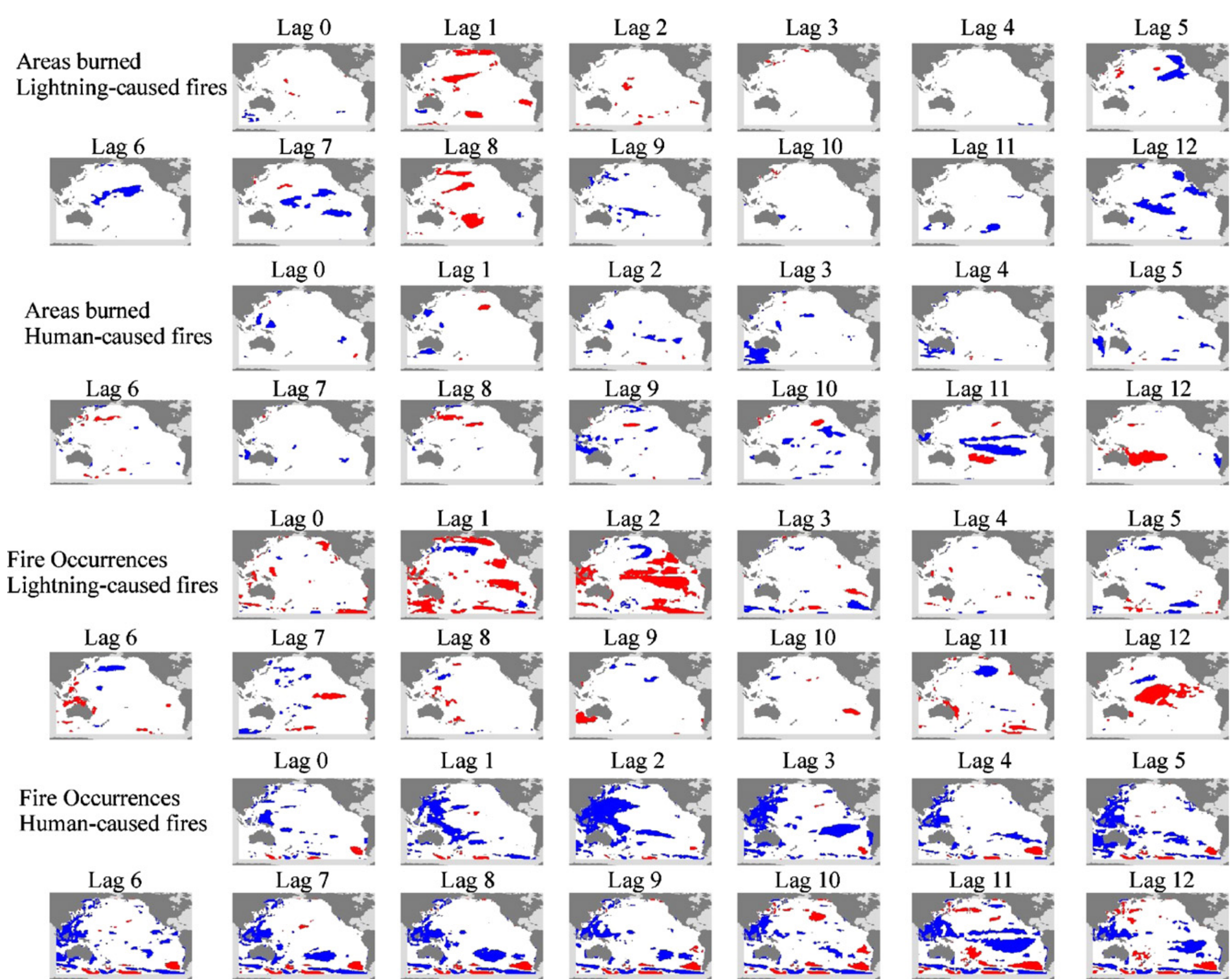

Fig. 5. Significant correlations between the four fire variables and annual mean anomalies in sea surface temperature for the current year (lag 0) and for lags of 1–12 years. Red denotes a significant positive correlation, and blue denotes a significant negative correlation.

the grid cells with significant correlations ($p < 0.05$) for the four fire variables are shown in Fig. 5. The correlations between area burned by lightning-caused fires and SST were significant at lags of 1, 5 through 8, and 12 years for large areas of the ocean. In contrast, the correlations between area burned by human-caused fires and SST were generally weaker and less extensive. Significant correlations occurred at lags of 11 and 12 years for the human-caused area burned; this indicates that both areas burned and SST may possess similar periodic properties, and areas burned lag behind SST approximately a dozen years. Future investigation is needed to understand such a phenomenon. Generally as the lag value increases, the number of observations used in cross-correlation decreases. Hence, the results of cross-correlation with large lags tend to be less reliable than those with small lags, and we should emphasize the results of small lags. Significant correlations existed between the occurrence of lightning-caused fires and SST at lags of 1 and 2 years for large areas of the ocean, whereas significant correlations between the occurrence of human-caused fires and SST were extensive at several lags (e.g., 2 years).

Using the data shown in Fig. 5, we calculated the percentage of the total area (or number of grid cells) within the study region for which significant correlations between SST and fire variables were recorded (Fig. 6). We used this information to examine lag-related temporal patterns in correlations. Overall, fire occurrence appeared to be more extensively correlated with SST than was area burned; in particular, for a lag period of 2 years, significant correlations occurred over more than 27% of the study region. In contrast, significant correlations for area burned were recorded for only about 10% of the study area (for all time lags).

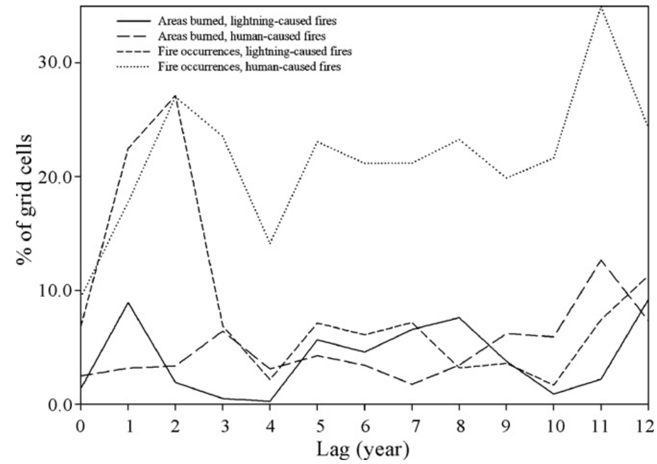

Fig. 6. Percentage of the grid cells for the study area for which annual mean anomalies in sea surface temperature were significantly correlated with the four fire variables.

It is possible that the significant correlations observed in this study were spurious. To validate our results and confirm that they

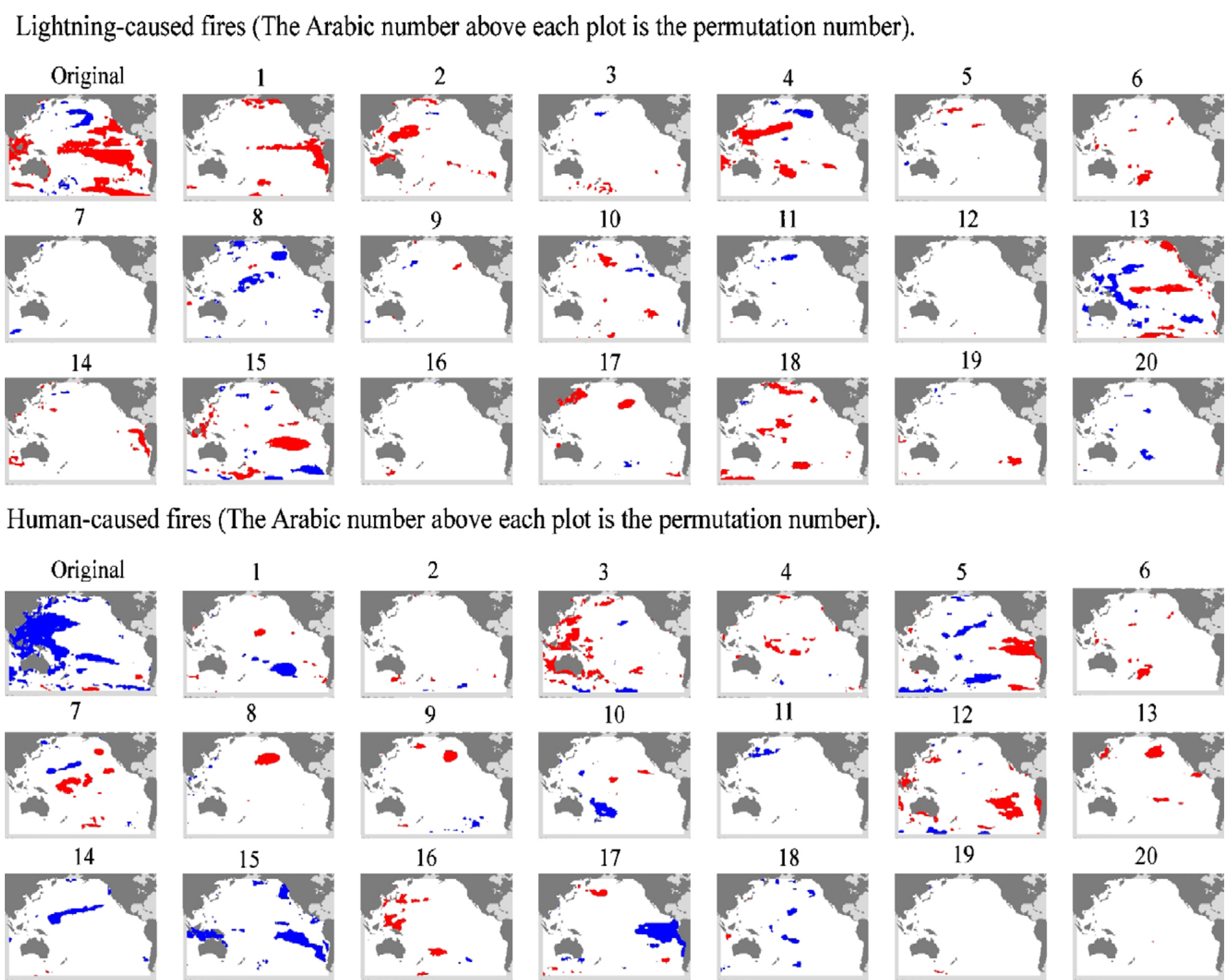

Fig. 7. Correlation between sea surface temperature and 20 randomly permuted fire occurrences for lightning-caused (top) and human-caused (bottom) fires, at a lag of 2 years.

were not due to chance, we considered the correlations between fire occurrence and SST for both lightning- and human-caused fires with a lag of 2 years. For these two cases, the analyses were re-run, with the original fire series being replaced by randomly permuted versions, which were known to have no teleconnection with the SSTs. The random permutation test was repeated 20 times for each type of fire (lightning- and human-caused). If the spatial correlation patterns for the 20 tests were similar to the patterns obtained with the original occurrence data, the observed correlations could be interpreted as spurious, which would lead, in turn, to the conclusion that the apparent teleconnection is not real. Otherwise, the observed correlation patterns would be interpreted as genuine, and the teleconnection between the Pacific SST and BC fires could be concluded to exist. The results of these analyses (Fig. 7) clearly indicate that the correlation patterns did not occur by chance alone. In a further effort to assess the validity of the correlations, we calculated the percentages of grid cells in the study region for which both the original and the permuted fire occurrences were significantly correlated with SST. For the original data, 27% of grid cells for both human- and lightning-caused fires had significant correlation, but for the permuted data, an average of only 4.7% (standard deviation 4.6) of cells for lightning-caused fires and 5.1% (standard deviation 4.0) of cells for human-caused fires had significant correlations. This comparison provides further evidence that the correlations based on the original data were not due to chance.

As a complement to our spatial correlation analysis, we calculated cross-correlations between fire activity and the annual Niño 3.4, PDO, and AO indices for the same period (Fig. 8) using the PROC TIMESERIES procedure in SAS/ETS. A cross-correlation was considered significant if its absolute value was greater than twice the standard deviation. According to this definition, the occurrences of lightning-caused fire were significantly correlated with the Niño 3.4 index at lag 2 (Fig. 8A). The occurrence of lightning-caused fires was also significantly correlated with the PDO index for lags 1 and 2, and the correlation of this fire variable with the PDO index was consistently greater than that of the other fire variables (Fig. 8B). A significant correlation existed between the occurrence of lightning-caused fires and the AO in the same year (i.e., without a lag). The correlation between the occurrence of human-caused fires and AO was similar for the longer lags, from 7 to 11 years (Fig. 8C). These results support the results of the spatial data analysis indicating that correlations between fire occurrence and climate are stronger than those between area burned and climate.

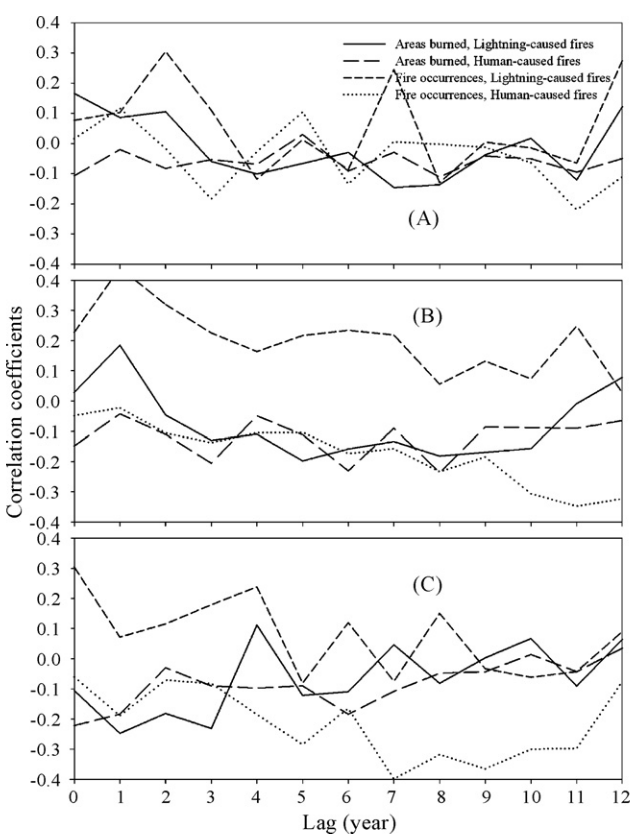

Fig. 8. Cross-correlations between the four fire variables and three commonly used indices of the Niño 3.4 index (A), the Pacific Decadal Oscillation index (B), and the Arctic Oscillation index (C).

4. Conclusion

Significant correlations exist between the occurrence of forest fire in British Columbia and the SST for large areas of the Pacific Ocean. The evidence presented here supports our hypothesis that the Pacific SSTs or even the El Niño, PDO, or AO signals are connected in some way with the fire activity in British Columbia, but the connections differ for fire occurrence and area burned. These results indicate a lag in the effects of the Pacific SST, whereby climatic conditions in previous years have a greater impact on current fire activities than do current conditions. Specifically, SST conditions in the previous year or two appeared to have the strongest influence on annual fire occurrence. A period of 12 years was the maximum lag examined; however, the cross-correlation results became less reliable as the lag period increased. Weak correlations between area burned and SST may be attributed to the fact that more than 85% of the province's forests are under various forms of fire-protection, such that suppression activities are usually applied as soon as fires are detected. Hence, human activities have a decisive impact on the area burned by both lightning-caused and human-caused fires. Martell and Sun (2008) found a statistically significant relation between the area burned due to lightning-caused fires and the fire-suppression effort applied to fires in another Canadian province (Ontario). Conversely, humans have almost no control over fire ignitions caused by lightning, which may explain why the occurrence of lightning-caused fires was so strongly correlated with SSTs.

Cold temperatures in the western Pacific would support the development of a high-pressure ridge over the western coast of North America, which could result in unseasonably warm temperatures, lower precipitation, and perhaps an earlier spring, which would be conducive to recreational use of the forest and to the high probability of human-caused fire occurrence. The lag effects may indicate drought conditions in the years just before the current fire season. The results of this study support our hypothesis that certain teleconnections exist between fire activities in BC and the Pacific SST. Significant correlations between the fire variables and SSTs suggest that linear regression models or other regression techniques might be suitable for predicting the severity of fire seasons using the SSTs of previous years as the independent (predictor) variable.

Relationships between wildfires and climate variability have been analyzed previously. Skinner et al. (2006) examined the relationship between variation in peak severity of the Canadian forest fire season and variations in SST during the previous winter. Gan (2006) used Pacific SST represented by ENSO indexes to demonstrate the applicability of vector autoregression modeling in probing the causality relationship among wildfire, Pacific SST, timber harvest, and urban sprawl in the U.S. Ni et al. (2006) used a simulation model to study vegetation dynamics in northern Africa and China. They found that climate variability affected vegetation through drought stress, which changed fuel availability in semi-arid regions where lack of fuel affected fire occurrence.

Loehle and LeBlanc (1996) conducted a critical review of the models to assess climate change effects on forests, and identified three approaches: Ecological Response Surface Models in which the abundance of tree species is used to calibrate multiple regression functions versus climate variables (e.g., White et al., 2008); Forest Stand Simulation (Gap) Models which are widely used tools for assessing climate change effects on forests (e.g., Zhang et al., 2008; Ni et al., 2006), and Biogeographic Correlations that examine climate change effects on forests using correlations between climate conditions and spatial distribution of vegetation characteristics (in our case forest fire activities were used).

Generally, our model and the models by Skinner et al. (2006) and Gan (2006) belong to the approach of Biogeographic Correlations, although mathematical details are different among the models. Canonical correspondence analysis and ensemble method (e.g., van der Schrier et al., 2007) are used in the model of Skinner et al. (2006); in their model the multivariate correlation tool of canonical correlation plays an important role. The vector autoregression model of Gan (2006) allows for multi-directional and multi-faceted interactions among the variables concerned, and it reflects the temporal impacts of ENSO and other variables on wildfire. In contrast, our model is more straightforward; only correlation and cross-correlation are used. The advantages of our model are its simplicity and its ability to show the spatial correlation pattern in the Pacific. The purpose of our modeling exercise is to find if significant correlation exists between the Pacific SST and fires in British Columbia, and such information may provide information for developing regression models to predict current and future fire activity from previous years' SSTs. Test results indicate that the model is suitable for this purpose. However, as the correlation is calculated cell by cell independently, the spatial relationships among the SST cells are not fully utilized. Although the model of Ni et al. (2006) involves climate variability and wildfire, the model they used is a pre-developed model of simulating ocean-atmospheric circulation, and it belongs to the simulation approach (Loehle and LeBlanc, 1996).

Although teleconnections exist between Pacific SST and BC fires, it should be pointed out that it is beyond the scope of this study to discuss the potential physical linkages between Pacific SST variability, atmospheric circulation, and forest fire activity in BC. Correlation analyses as conducted expose certain connections between SST and BC fires; however, finding the mechanisms that underlie the connections will require more effort in the future. For example, as the lightning-caused fire occurrence are directly related to the weather conditions in BC, future work could be focused on the mechanism between the Pacific SST variability and the long-term changes of BC's climate and weather.

References

Balzter, H., Gerard, F.F., George, C.T., Rowland, C.S., Jupp, T.E., McCallum, I., Shvidenko, A., Nilsson, S., Sukhinin, A., Onuchin, A., Schmullius, C., 2005. Impact of the Arctic Oscillation pattern on interannual forest fire variability in Central Siberia. Geophys. Res. Lett. 32, L14709, doi:10.1029/2005GL022526.

BC Ministry of Forests and Range, 2007. http://www.gov.bc.ca/for/.

Bottomley, M., Folland, C.K., Hsiung, J., Newell, R.E., Parker, D.E., 1990. Global Ocean Surface Temperature Atlas (GOSTA). Meterological Office (UK), London, 20 + iv pp., 313 plates.

Brenner, J., 1991. Southern Oscillation anomalies and their relationship to wildfire activity in Florida. Int. J. Wildland Fire 1, 73–78.

Bunkers, M.J., Millar Jr., J.R., deGaetano, A.T., 1996. An examination of El Niño-La Niña-related precipitation and temperature anomalies across the northern plains. J. Clim. 9, 147–160.

Deser, C., Blackmon, M.L., 1995. On the relationship between tropical and north pacific sea surface temperature variations. J. Clim. 8, 1677–1680.

Flannigan, M.D., Harrington, J.B., 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada 1953–80. J. Appl. Meteorol. 27, 441–452.

Gan, J., 2006. Causality among wildfire, ENSO, timber harvest, and urban sprawl: the vector autoregression approach. Ecol. Model. 191, 304–314.

Greer, I.W. (Ed.), 1996. Glossary of Weather and Climate with Related Oceanic and Hydrologic Terms. American Meteorological Society, Boston.

Horel, J.D., Wallace, J.M., 1981. Planetary-scale atmospheric phenomena associated with the Southern Oscillation. Mon. Weather Rev. 109, 813–829.

Johnson, E.A., 1992. Fire and Vegetation Dynamics: Studies from the North American Boreal Forest. Cambridge University Press, Cambridge.

Loehle, C., LeBlanc, D., 1996. Model-based assessments of climate change effects on forests: a critical review. Ecol. Model. 90, 1–31.

Martell, D.L., Sun, H., 2008. The impact of fire suppression, vegetation, and weather on the area burned by lightning-caused forest fires in Ontario. Can. J. For. Res. 38, 1547–1563.

Ni, J., Harrison, S.P., Prentice, I.C., Kutzbach, J.E., Sitch, S., 2006. Impact of climate variability on present and Holocene vegetation: a model-based study. Ecol. Model. 191, 469–486.

Reynolds, R.W., Rasmusson, E.M., 1982. The North Pacific sea surface temperature associated with El Nino events. In: Proceedings of the 7th Annual Climate Diagnostics Workshop. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, and National Center for Atmostheric Research, Boulder.

Reynolds, R.W., Rayner, N.A., Smith, T.M., Stokes, D.C., Wang, W., 2002. An improved in situ and satellite SST analysis for climate. J. Clim. 15, 1609–1625.

Reynolds, R.W., Smith, T.M., 1995. A high resolution global sea surface temperature climatology. J. Clim. 8, 1571–1583.

SAS Institute Inc., 2004. SAS/ETS 9.1® User's Guide. SAS Institute Inc., Cary, NC.

Shabbar, A., Bonsal, B., Khandekar, M., 1997. Canadian precipitation patterns associated with the Southern Oscillation. J. Clim. 10, 3016–3027.

Simard, A.J., Haines, D.A., Main, W.H., 1985. Relations between El Nino/southern Oscillation anomalies and wildland fire activity in the United States. Agric. For. Meteorol. 36, 93–104.

Skinner, W.R., Shabbar, A., Flannigan, M.D., Logan, K., 2006. Large forest fires in Canada and the relationship to global sea surface temperature. J. Geophys. Res. 111, D14106, doi:10.1029/2005JD006738.

Skinner, W.R., Stocks, B.J., Martell, D.L., Bonsal, B., Shabbar, A., 1999. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. Theor. Appl. Climatol. 63, 89–105.

Smith, T.M., Reynolds, R.W., 2004. Improved reconstruction of SST (1854–1997). J. Clim. 17, 2466–2477.

Swetnam, T.W., 1993. Fire history and climate change in giant sequoia groves. Science 262, 885–889.

Swetnam, T.W., Betancourt, J.L., 1990. Fire-Southern Oscillation relations in the southwestern United States. Science 249, 1017–1020.

Thompson, D.W.J., Wallace, J.M., 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett. 25, 1297–1300.

Trenberth, K.E., 1990. Recent observed interdecadal climate changes in the northern hemisphere. Bull. Am. Meteorol. Soc. 71, 988–993.

Trenberth, K.E., 1997. The definition of El Niño. Bull. Am. Meteorol. Soc. 78, 2771–2777.

Trenberth, K.E., Stepaniak, D.P., 2001. Indexes of El Niño evolution. J. Clim. 14, 1697–1701.

van der Schrier, G., Osborn, T.J., Briffa, K.R., Cook, E.R., 2007. Exploring an ensemble approach to estimating skill in multiproxy palaeoclimate reconstruction. Holocene 17, 119–129.

White, T., Luckai, N., Larocque, G.R., Kurz, W.A., Smyth, C., 2008. A practical approach for assessing the sensitivity of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). Ecol. Model. 219, 373–382.

Williams, A.A.J., Karoly, D.J., 1999. Extreme fire weather in Australia and the impact of the El Niño–southern Oscillation. Aust. Meteorol. Mag. 48, 15–22.

Zhang, J., Chu, Z., Ge, Y., Zhou, X., Jiang, H., Chang, J., Peng, C., Zheng, J., Jiang, B., Zhu, J., Yu, S., 2008. TRIPLEX model testing and application for predicting forest growth and biomass production in the subtropical forest zone of China's Zhejiang province. Ecol. Model. 219, 264–275.

Zhang, Y., Wallace, J.M., Battisti, D.S., 1997. ENSO-like interdecadal variability. J. Clim. 10, 1004–1020.