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IMPACTS OF LARGE-SCALE ATMOSPHERIC–OCEAN VARIABILITY ON ALASKAN FIRE SEASON SEVERITY

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Abstract. Fire is the keystone disturbance in the Alaskan boreal forest and is highly influenced by summer weather patterns. Records from the last 53 years reveal high variability in the annual area burned in Alaska and corresponding high variability in weather occurring at multiple spatial and temporal scales. Here we use multiple linear regression (MLR) to systematically explore the relationships between weather variables and the annual area burned in Alaska. Variation in the seasonality of the atmospheric circulation–fire linkage is addressed through an evaluation of both the East Pacific teleconnection field and a Pacific Decadal Oscillation index keyed to an annual fire index. In the MLR, seven explanatory variables and an interaction term collectively explain 79% of the variability in the natural logarithm of the number of hectares burned annually by lightning-caused fires in Alaska from 1950 to 2003. Average June temperature alone explains one-third of the variability in the logarithm of annual area burned. The results of this work suggest that the Pacific Decadal Oscillation and the East Pacific teleconnection indices can be useful in determining a priori an estimate of the number of hectares that will burn in an upcoming season. This information also provides insight into the link between ocean–atmosphere interactions and the fire disturbance regime in Alaska.

Key words: *Alaska boreal forest; East Pacific teleconnection; ecological disturbance regimes; fire regimes; multiple linear regression; Pacific Decadal Oscillation; teleconnections.*

Introduction

The boreal forest covers 12×10^6 km^2 of the northern hemisphere and contains roughly 40% of the world's reactive soil carbon, an amount similar to that held in the atmosphere (Melillo et al. 1993, McGuire et al. 1995, IPCC 2001). The biophysical phenomena affecting carbon storage and high-latitude albedo make the boreal forest an integral component of the global climate system (IPCC 2001). Fire-initiated succession underlies the biophysical factors, and there is a pressing need to characterize sensitivities and potential responses of the boreal forest disturbance regime to climatic change (Schimel et al. 1997, Gower et al. 2001, Chapin et al. 2003). The impact of forecast climatic warming on fire regimes in North America varies from a prediction for increased burning for Alaska and Canada (Flannigan et al. 2000, 2001) to reduced fire frequency in eastern Canada (Carcaillet et al. 2001). Quantification of the links between climate and fire in Alaska is not only essential for understanding the dominant landscape-scale disturbance processes in Alaska, but it is also a valuable tool for planning fire management activities and developing a better understanding of how forecast climate change might impact the dominant disturbance mechanism.

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Within the North American boreal forest, Interior Alaska (i.e., the region between the Alaska and Brooks Ranges) contains 56×10^6 burnable hectares and includes the largest national parks and wildlife refuges in the United States. Most of this huge area is roadless. For the period 1950–2003, wildland fires burned an average of roughly 270 000 ha in Interior Alaska each year and they routinely threaten the lives, property, and timber resources of the sparse but growing population (see Plate 1). Wildland fires can threaten human values, yet they play a crucial role in the maintenance of Interior Alaskan ecosystems. Despite the pervasive economic and ecological impacts, fundamental aspects of the fire regime in Interior Alaska are poorly understood.

Fire regimes consist of many components including frequency, duration, intensity, severity, seasonality, extent, and spatial distribution. When complicating factors such as interactions with other components of the ecosystem (e.g., human impacts, weather, vegetation) and the importance of spatial and temporal scales are taken into account, the characterization of a fire regime requires a tremendous amount of data and appropriate analysis. One of the most basic aspects of a fire regime is the fire cycle (i.e., the fire recurrence interval for an

PLATE 1. The Long Creek fire of 2002, near Ruby, Alaska. Fire is the dominant landscape-scale disturbance mechanism in Interior Alaska. Photo credit: T. S. Rupp.

area equivalent to the study area). There are only a few field studies from Interior Alaska that utilize fire-scar and/or tree age distributions to infer fire cycle (Yarie 1981, DeVolder 1999, Mann and Plug 1999). These studies were scattered over a region the size of Montana and show that fire cycles in Alaska are probably >250 years in the relatively moist, southern parts of the state (D. H. Mann, *personal communication*), 80–100 years near Fairbanks in the central Interior (Mann et al. 1995), and <80 years for the Porcupine River valley in the northeastern portion of the state (Yarie 1981). These estimates are consistent with the results of Kasischke et al. (2002), who used fire perimeter data (from aerial photography and remotely sensed data) from the past five decades to estimate fire cycles for different ecoregions of the interior. The uncertainty associated with these fire cycle estimates is unknown.

At longer temporal scales but somewhat more coarse resolution, charcoal and pollen analyses from varved lake sediments reveal critical information about the fire frequency and interactions between fire, climate, and vegetation. Due to the limited dispersal of charcoal particles that are used in these analyses, the results apply to limited spatial scales. Within Interior Alaska, there have only been a few studies that utilize sediment cores to gain insight about the fire regime. Pollen and charcoal data from several sediment cores in Interior Alaska reveal that shifts in vegetation (i.e., increased dominance of *Picea mariana*) around 2400 yr BP are associated with a corresponding shift in the fire regime (Lynch et al. 2003). The implication is that climatic change occurring at decadal to centennial timescales influenced the fire regime through shifts in dominant vegetation. This yields the counterintuitive result that cooler and moister climate results in higher fire frequency due to the increased dominance of the relatively more flammable *Picea mariana*. This response appears to extend outside Interior Alaska to forests south of the Alaska Range as well (Lynch et al. 2004). These studies provide evidence that climatically induced shifts in dominant vegetation within the boreal forest over a period of decades to centuries can potentially modify the fire regime. Outside of Alaska in the Canadian boreal forest, there is evidence that, on timescales of hundreds to thousands of years, climate has a more direct influence on fire regime (Carcaillet and Richard 2000, Carcaillet et al. 2001). Hence, climate differentially exerts influences on both vegetation composition and fire regime, depending on the location within the boreal forest as well as the resolution of the timescale of interest.

As a mechanism that modifies atmospheric circulation patterns at large spatial scales, atmospheric teleconnections affect weather throughout the northern hemisphere (Hurrell et al. 2003). Teleconnections are correlated anomalies of geopotential height (Wallace and Gutzler 1981, Barnston and Livezey 1987) that impact regional weather through recurring and persistent shifts in pressure and circulation across large spatial scales. Links between disturbance and weather that are mediated by teleconnections include; droughts and fire in Canada (Bonsal et al. 1993, Bonsal and Lawford 1999, Skinner et al. 2002, Girardin et al. 2004), fires in the Pacific Northwestern United States (Hessl et al. 2004) and fires in the Southwestern United States (Swetnam and Betancourt 1990). In Alaska, deviations from synoptic weather patterns have been correlated with the Pacific Decadal Oscillation (Papineau 2001, Hartmann and Wendler 2003) as well as the El Niño/Southern Oscillation and Pacific/North America patterns (Hess et al. 2001). Specifically, the occurrence of large fire years has been correlated with the presence of strong to moderate El Niño conditions (Hess et al. 2001). Our work moves a step further and quantifies the impact of these signals on the annual area burned in Alaska through the development of a statistical regression model.

Experience and common sense dictate that fire responds to local weather conditions, but modeling results indicate that the link between weather and fire does not easily translate to the landscape scale (Flannigan and Harrington 1988, Hely et al. 2001, Westerling et al. 2002). Yet at large spatial scales, statistical relationships quantifying these links at an annual temporal resolution in Alaska have not been established. It is important to stress the spatiotemporal scale at which this analysis is relevant, since the dynamics of interactions between climate, fire, and vegetation change depend on the spatial and temporal scale of interest. This work quantifies the relationship between monthly teleconnection indices, specifically the East Pacific teleconnection and the Pacific Decadal Oscillation, and the annual area burned by lightning-caused fires in Alaska through the development of a statistical regression model. To this end, a Multiple Linear Regression (MLR) model is developed, with the natural logarithm of the number of hectares burned annually as the response variable and monthly climatic indices for explanatory variables. We used a sequential selection procedure to evaluate linkages between teleconnection indices and monthly temperature and precipitation. In doing so, we characterize the linkages between components of the climate system that exert an influence on short-term surface weather in Alaska. The statistical model presented in this work represents a simple first step in quantifying the complex linkages between climate and fire in Interior Alaska, where fire is the dominant agent of landscape-level change (Van Cleve et al. 1991, Payette 1992) and dictates the composition of the forest vegetation through determination of the successional trajectory (Zackrisson 1977, Van Cleve and Viereck 1983, Payette 1992, Mann and Plug 1999).

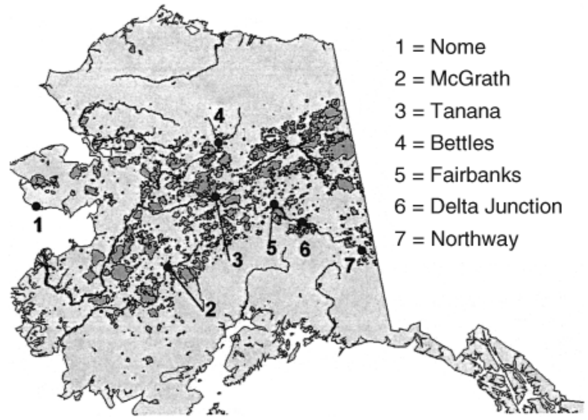

FIG. 1. Map of Alaska, USA, identifying the seven climate stations used in the statistical analyses. The enclosed areas with darker shading represent individual fire perimeters from 1950 to 2003.

METHODS

Fire data

The Alaska Fire Service (AFS) maintains a database of fires for the state of Alaska dating back to 1950. These data are commonly referred to as the Large Fire Data Base (LFDB) and can be found at the Alaska Geospatial Data Clearinghouse (AGDC; *available online*)[6] (Kasischke et al. 2002). The period of analysis for our study is 1950–2003 (Fig. 1). For each year and for each fire recorded in the AGDC, there are many pieces of information recorded, including ignition source (i.e., human or lightning) and a record of the approximate size of each fire. Estimates of the annual number of hectares burned in Alaska that are used in this analysis come from summing the number of hectares burned from each lightning-caused fire within a given year. Because lightning is the natural ignition source, part of the climate–fire link includes the climatic conditions that are favorable for lightning-caused ignitions (Johnson 1992, Nash and Johnson 1996, Wierzchowski et al. 2002). Lightning-caused fires are rare both north of the Brooks Range, and south of the Alaska Range, and as a consequence the majority of fires burn between these mountain ranges within the region known as Interior Alaska (Fig. 1).

Human-caused fires were excluded, since the analysis is focused on the link between climate and fire. Historically, the exclusion of human-caused fires has a relatively small impact on the number of hectares burned annually. However, in 2001 and 2002, over 95% and 40% of the respective area burned was caused by nonlightning ignition sources. Another factor to consider regarding the use of the LFDB is that reliability

[6] ⟨http://agdc.usgs.gov/data/blm/fire/index.html⟩

of source determination can reasonably be assumed to be more questionable for the early part of the record. Only fires that burned an area >50 ha (0.5 km^2) were included in the analysis. This was done so that the results of this work could be used in conjunction with the frame-based spatially explicit ecosystem model ALFRESCO (Starfield and Chapin 1996, Rupp et al. 2000), which operates on a spatial resolution of 1 km^2. The exclusion of fires <50 ha (0.5 km^2) has a negligible impact on the output of the statistical model.

Climate data

Alaskan climate station data that are both homogeneous and complete for the past half-century are sparse. Data were obtained from the Western Region Climate Center (WRCC; *available online*).[7] There are fewer than a dozen climate stations in Alaska with sufficient data for our modeling purposes (Fig. 1). The requirement for selection of a climatic station was that no more than 5% of the monthly observations from 1950 to 2003 were missing. Based on this selection criterion and spatial representativeness with respect to fires that have burned over the period of record, the following seven stations were used: Bettles, Delta Junction, Fairbanks, McGrath, Nome, Northway, and Tanana (Fig. 1).

The question of how to represent both the temperature and precipitation of Alaska based on these seven stations is not a trivial one. We are essentially determining from a small number of stations a spatial zone of weather influence for the area burned annually in Alaska. Several methods for calculating representative weather were evaluated. Different weighting schemes for the climate data were considered based on the spatial location of fires for a given year. As an example, if the majority of fires burned near Tanana in a given year, then a weighting scheme would give the data from Tanana greater weight than the other six stations when assembling the weather data for that year. Of the different methods evaluated for assembling the climate data, the simplest and most effective in terms of explaining the greatest variability was a simple average of the data for a given month from the seven stations. This results in a ''statewide'' average of both temperature and precipitation for each month in a given year. This procedure essentially integrates any spatial information regarding intrastate variability over Interior Alaska into a single estimate. For each station, the average monthly temperatures from the WRCC are calculated as the average of all the average daily temperatures in a given month. The monthly precipitation for each station was calculated as the sum of the precipitation amounts recorded daily at each station for each day in the month. The average monthly precipitation for the MLR was then taken to be the average of the monthly precipitation recorded for each of the seven stations.

Additionally, we refit our regression model using monthly temperature and precipitation data from the Climate Research Unit (CRU) in place of the seven-station average. The CRU data consist of data-based model estimates of monthly temperature and precipitation values for half-degree cells and are a distance-weighted average of all available station data in Alaska. Hence, a different number of stations are used depending on which data are available for a given month. We averaged the monthly values for cells covering the region of Interior Alaska where fires burn (Fig. 1) to produce a CRU-based data set that is capable of driving our statistical model. The reduction in variability explained by the statistical model when the CRU data set is used was <5%. This shows that the results of the regression model are robust with respect to the method of spatially integrating the climate data, and it also shows that the simple seven-station average does a better job of representing the weather signals that explain interannual variability in area burned.

East Pacific (EP) teleconnection data

Monthly teleconnection indices were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC; *available online*).[8] Each teleconnection identified by the CPC (e.g., the North Atlantic Oscillation, East Atlantic, East Atlantic Jet, East Atlantic/Western Russia, Scandinavian, Polar/Eurasia, Asian Summer, West Pacific, East Pacific, North Pacific, Pacific/North America, Tropical/Northern Hemisphere, and the Pacific Transition) was evaluated for its ability to explain variability in the natural logarithm of the number of hectares burned annually in Alaska. The monthly indices for the East Pacific (EP) teleconnection collectively explained the greatest amount of variability. Since the EP has a strong center near Alaska and a comparable but oppositely signed locus between Hawaii and the Baja peninsula (Fig. 2, after Barnston and Livezy 1987), this finding is physically plausible. Strong positive phases of the EP pattern are associated with upper airflow that is more meridional over the northeastern Pacific. This results in enhanced ridging over Alaska and the western coast of North America. Alternatively, negative phases of the EP pattern are associated with increased zonal flow and strengthened westerlies in the Eastern North Pacific as a consequence of negative height anomalies to the north and positive anomalies to the south of 40°–45° N. The negative phase is also associated with an eastward displacement of the Aleutian Low (AL), in the North Pacific.

Pacific Decadal Oscillation

Significant covariability exists between Sea Surface Temperatures (SSTs) and North American climate

[7] ⟨http://www.wrcc.dri.edu/summary/climsmak.html⟩

[8] ⟨http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html⟩

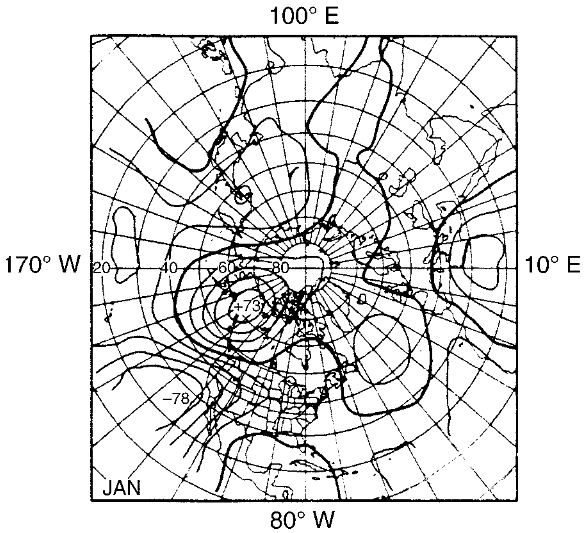

FIG. 2. East Pacific Pattern in January, adapted from Barnston and Livezy (1987). Values are correlations between 70 kPa (700 millibar) heights at grid points and the rotated principal-component time series of the East Pacific teleconnection. The 70 kpa heights approximate the actual height of a pressure surface above mean sea level. These heights correspond to the middle troposhere at roughly 3000 m. Height anomalies at the 70-kPa level influence the movement of surface weather systems.

(Bonsal et al. 1993, Livezy and Smith 1999). Specifically, there is correlation between SSTs in the North Pacific and weather in Alaska (Papineau 2001). The Pacific Decadal Oscillation reflects differences in the circulation and location of anomalous warm/cool SSTs across the Pacific Ocean. (An image of typical wintertime sea surface temperature, sea level pressure, and surface windstress anomaly patterns during both warm and cool phases of the Pacific Decadal Oscillation has been created by Steven Hare, International Pacific Halibut Commission [*available online*].)[9] To quantify the impact of North Pacific SSTs on area burned in Alaska, indices for the Pacific Decadal Oscillation (PDO; *available online*)[10] were examined as explanatory variables in the MLR. Multiple temporal scales (i.e., one, two, three, and four-month averages) of the PDO index were evaluated as explanatory variables in the MLR model. Some degree of statistical similarity exists between the signal for the PDO and El Niño events. Because of this similarity, El Niño indices (both pressure-based and SST) were evaluated for their potential as explanatory variables in the statistical model. The metric used to quantify the PDO was more statistically significant.

Depending on the phase of the PDO, certain atmospheric circulation patterns in the North Pacific are favored. During cool phases of the PDO, ridging is more frequent, whereas in the warm phase, the development of troughs is more likely (Bond and Harrison 2000). The cool phase is characterized by cool SSTs in the Gulf of Alaska (GOA) and warm temperatures in the North Pacific. Alternatively, warm SSTs in the GOA and cool temperatures in the North Pacific characterize the warm phase of the PDO. The strength and location of the AL is also correlated with the phase of the PDO. During cool phases of the PDO, the AL is, on average, located around the western extent of the Aleutian Islands. When the PDO shifts from a cool phase to a warm phase, the AL strengthens and moves to the east (Trenberth 1992, Niebauer 1998).

Statistical model and spatiotemporal scaling

The allowable number of explanatory variables in the MLR was fixed at roughly 15% of the total number of data points. Standard subset selection techniques were used to evaluate significance of monthly temperature/precipitation and teleconnection indices within the MLR model. By fixing the number of parameters, we are essentially evaluating a subset of all possible models. In the context of information criteria (e.g., AIC) we have fixed the penalty function and are maximizing the likelihood within this subset of models. There are numerous methods with differing criteria that can be used to fit models. The success of any model selection exercise can best be evaluated by crossvalidation. The results of sequential crossvalidation along with other model diagnostics (e.g., residual analyses) show that the regression model is relatively robust and does not violate any of the regression assumptions.

The natural logarithm transformation is applied to the data for annual area burned to both minimize heteroscedasticity and decrease the potential for bias in variable selection based on the relatively small number of years where the majority of area burned. This transformation results in more reliable tests of parameter significance, since the variability of the response is no longer a nonconstant function of the expected value estimated by the regression. All references to statistical significance are made at the 0.10 Type I error level.

The spatial and temporal scales of the MLR need to be considered when interpreting the results. The statistical model is essentially a point model in that it integrates values of climatic explanatory variables across both space (i.e., Interior Alaska) and time. The model integrates across space through the calculation of a simple average of monthly climate indices for weather stations that in this sense represent Interior Alaska (Fig. 1). This method represents a first-order integration of spatial information regarding intrastate variability into a single point estimate. The model integrates across time through the use of monthly averages for the temporal scale of explanatory variables and the use of annual values for response variables. The use of monthly indices lacks explicit consideration of intramonthly variability. Extreme fire behavior can and often does occur at a less than monthly temporal

[9] ⟨http://tao.atmos.washington.edu/pdo/img/pdo_warm_cool.tif⟩

[10] ⟨http://jisao.washington.edu/pdo/PDO.latest⟩

TABLE 1. Statistical output for the multiple linear-regression (MLR) model with the natural logarithm of the number of hectares burned annually as the response variable.

Explanatory variable	Estimate	SE	t	P
Intercept	−41.368	7.352	−5.626	1.12×10^{-6}
Average June temperature	0.617	0.098	6.302	1.11×10^{-7}
DEP	−4.803	0.914	−5.254	3.93×10^{-6}
Average April temperature	−0.199	0.041	−4.855	1.49×10^{-5}
DEP × average April temperature	0.159	0.034	4.712	2.38×10^{-5}
Average May temperature	0.235	0.056	4.201	1.24×10^{-4}
Average PDO of January and February	−0.465	0.151	−3.071	3.61×10^{-3}
Average July temperature	0.252	0.089	2.836	6.81×10^{-3}
Average June precipitation	−1.195	0.458	−2.606	1.24×10^{-2}

Notes: Residual SE = 1.098; df = 45. $F_{8, 45} = 21.14$, $P = 7.112 \times 10^{-13}$. The R^2 value of 0.79 implies that the deterministic component of the MLR (consisting of the explanatory variables listed) model explains 79% of the total variability in the response variable. See Table 3 for a key to the abbreviations.

scale (Flannigan and Harrington 1988, Alvarado et al. 1998). Nonetheless, important linkages between pressure anomalies and fire behavior on monthly/seasonal timescales have been identified in Canada (Johnson and Wowchuk 1993, Skinner et al. 1999).

The goal of the statistical model is to identify variables that collectively explain the greatest amount of variability in the natural logarithm of the number of hectares burned for a given year. The structure and spatiotemporal scaling of the model were selected to be both pragmatic and parsimonious. Pragmatically, it is of interest to quantify the link between weather variables and the area burned for fire management activities and a greater understanding of fire–weather interactions. Another pragmatic aspect is that the antecedent nature of the various climatic variables gives the results application in long-range (monthly to seasonal) prediction of annual area burned in Alaska. As a starting point, integrating both the response and explanatory variables across space provides a clear definition of the spatial scale of interest and a simple interpretation of the model results. Across the numerous temporal scales evaluated, the current state of the model maximizes the predictive relationship between fire and climate.

RESULTS

Seven climatic variables and an interaction term collectively explain 79% of the variability in the natural logarithm of number of hectares burned annually. The explanatory variables in order of most to least significant (Table 1) are Average June Temperature (AJT), Delta EP Teleconnection (DEP), Average April Temperature, (AAT), the interaction between DEP and AAT, Average May Temperature (AMT), Average PDO index for January and February (PDOWIN), Average July Temperature (AJLT), and Average June Precipitation (AJP). DEP is defined as the January EP index minus the April EP index. The low P value for the F test (Table 1) indicates that the deterministic component of the statistical model explains a significant percentage of the variability in the natural logarithm of the number of hectares burned per year. Comparison between observed values of the number of hectares burned annually (Fig. 3, solid circles) and transformed model estimates (Fig. 3, solid diamonds with connecting lines) shows that the transformed estimates from the statistical model provide a reasonable estimate of the number of hectares burned annually. The estimated values (Fig. 3, solid diamonds with connecting lines) are an exponentiation of the fitted values produced by the MLR. Since the regression was performed on the natural logarithm of the number of hectares burned annually, a ''back-transformation'' was used to obtain estimates in the original space. There are numerous ways to ''back-transform'' data and this one, although the simplest, does produce a negatively biased estimate under the assumption of lognormality. Hence, predictions made

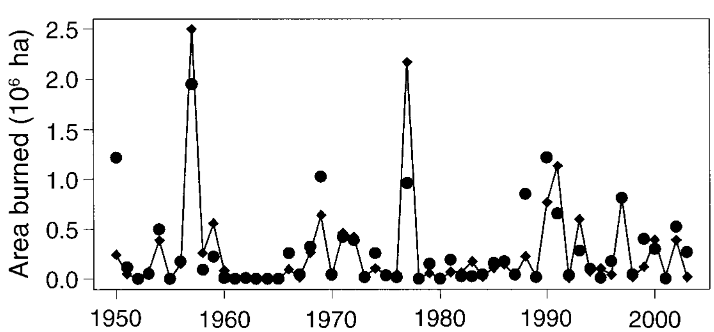

FIG. 3. Time series plot (years 1950–2003) showing the number of hectares burned annually (circles) and transformed estimates (diamonds with connecting lines) based on the predicted values from the multiple linear-regression (MLR) model. The estimated values (diamonds) in this plot are an exponentiation of the fitted values produced by the MLR. Since the regression was performed on the natural logarithm of the number of hectares burned annually, a ''back-transformation'' was used to obtain estimates in the original space.

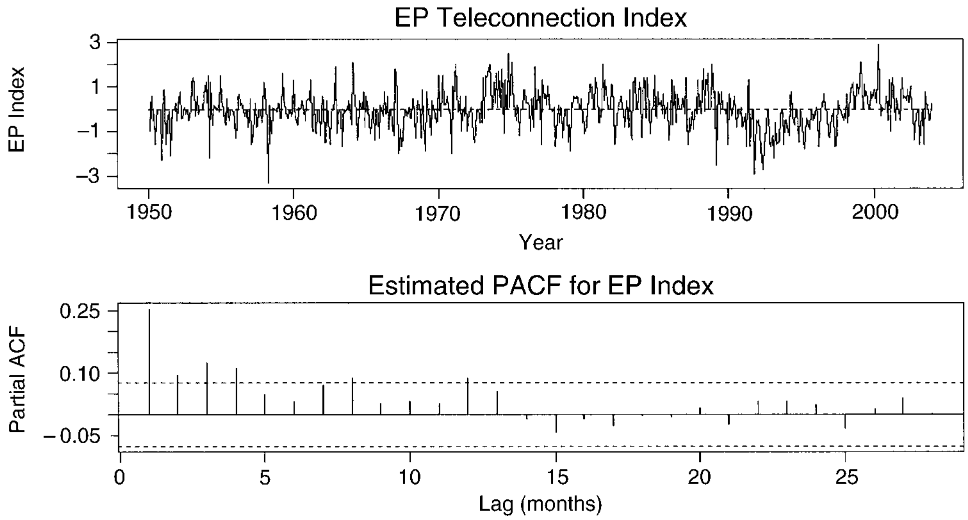

FIG. 4. Time series of East Pacific (EP) teleconnection index and estimated partial autocorrelation function (PACF) for the EP index. Dashed lines in the PACF plot represent 95% confidence intervals for the estimated correlation at a given lag.

using this simple back-transformation will produce slight underestimates under the assumption that the data for area burned are lognormally distributed.

Explanatory variables

Teleconnection indices.—The time series of the EP index (Fig. 4) and the estimated partial autocorrelation function shows that the EP teleconnection is an autoregressive process with maximal temporal correlations occurring at one- and three-month lags. DEP is defined as the January EP index minus the April EP index, and provides a metric of shifts in atmospheric circulation from winter to spring. Through its influence on atmospheric circulation, a shift from the negative phase of the EP index in winter to a positive phase in spring increases the likelihood of blocking ridges forming in the following summer. Hence negative values of DEP indicate a tendency toward drier-than-normal conditions for the months of March through August (Fig. 5). Along with drier-than-normal conditions, negative values of DEP are also associated with increased temperatures for the months of May and June (Fig. 6). The cumulative impact of the warmer and drier spring/summer conditions associated with negative values of DEP is a greater area burned (Table 2). The negative value of the parameter estimate for DEP (Table 1) implies that a shift from negative to positive EP values between

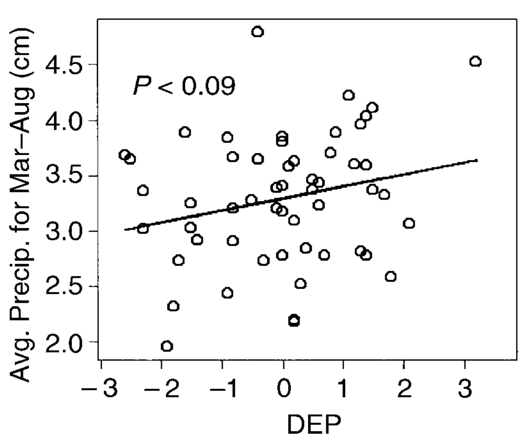

FIG. 5. Scatter plot of average precipitation for the months of March through August vs. DEP (January East Pacific teleconnection index minus April East Pacific teleconnection index). Shifts from negative values of the EP in January to positive values of the EP in April (negative DEP) are associated with decreased precipitation from March through August. The least-squares regression line and *P* value (corresponding to the test of slope equal to zero) are presented.

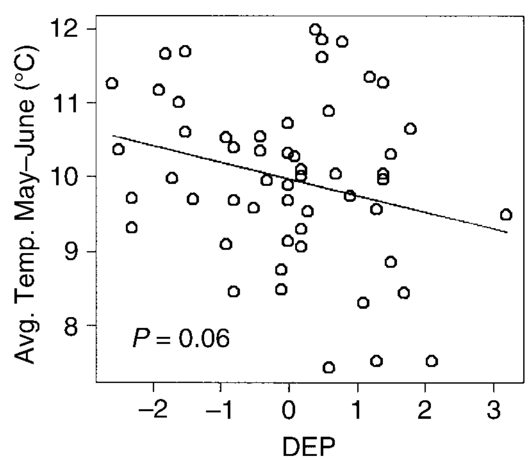

FIG. 6. Scatter plot of average spring (May and June) temperatures vs. DEP (January East Pacific teleconnection index minus April East Pacific teleconnection index). Shifts from negative values of the EP in January to positive values of the EP in April (negative DEP) are associated with increased temperatures in May and June. The least-squares regression line and *P* value (corresponding to the test of slope equal to zero) are presented.

TABLE 2. DEP data have been partitioned into ''big'' and ''small'' fire years with respect to 100 000 ha.

	Minimum	Median	Mean	Maximum
Small fire years	−1.50	0.60	0.64	3.20
Big fire years	−2.60	−0.65	−0.60	1.50

Notes: Years with area burned >100 000 ha are classified as ''big'' fire years, and years with area burned <100 000 ha are classified as ''small'' fire years. Positive values for DEP signify increased zonal flow from spring to summer, whereas negative values of DEP indicate more meridional flow and increased potential for ridges to develop (Figs. 5 and 6). DEP values for big fire years are significantly different (and less than) DEP values for small fire years ($P < 0.0002$ for Welsh's modification (unequal variances) to a two-sided, two-sample t test).

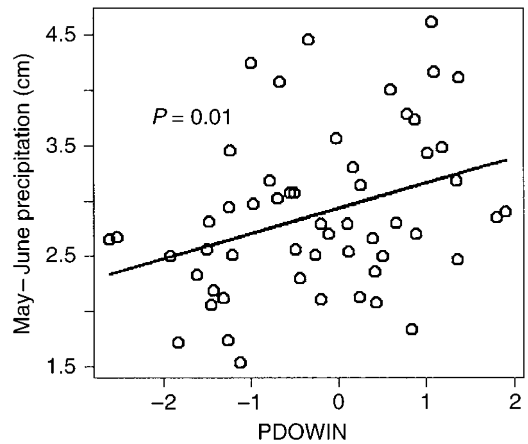

FIG. 7. Scatter plot of average precipitation for May and June vs. the average of the PDO index for the months of January and February. Cool phases of the PDO (negative PDOWIN) are associated with decreased precipitation for the months of May and June. The least-squares regression line and P value (corresponding to the test of slope equal to zero) are presented.

January and April favors a greater area burned in the upcoming summer.

Monthly PDO indices were evaluated for use as explanatory variables (Table 3) in the MLR, and winter indices displayed the largest signal with respect to explaining variability in the natural logarithm of the number of hectares burned annually in Alaska. The months of January and February were the most significant explanatory variables among the monthly PDO indices, and since the estimates were of the same sign, the average of these monthly indices (PDOWIN) was used as a single explanatory variable in the regression. The negative value for the parameter estimate of PDOWIN indicates that cool phases of the PDO are associated with a greater area burned. There is positive correlation between PDOWIN and the average precipitation for May and June (Fig. 7). Hence cool phases of the PDO are associated with drier summer conditions. Additionally, the phase of the PDO is also associated with a shift in the correlation between winter and summer precipitation. During the cool phase of the PDO, there is significant negative correlation between precipitation in summer and precipitation in winter, but no correlation exists during the warm phase (Fig. 8).

Temperatures.—The MLR analysis found the average temperatures for the months of April, May, June, and July (AAT, AMT, AJT, and AJLT, respectively) to be significant explanatory variables for the logarithm of the number of hectares burned (Table 1). Among the parameter estimates for these monthly temperatures only AAT has a negative value. AJT was the most significant explanatory variable identified by the MLR, and by itself it explains >34% of the variability in the response. Attempts to combine the average temperatures from months (across two-, three-, and four-month

TABLE 3. List of abbreviations.

Abbreviation	Variable
AAT	Average April Temperature
AGDC	Alaska Geospatial Data Clearinghouse
AFS	Alaska Fire Service
AMT	Average May Temperature
AJLT	Average July Temperature
AJT	Average June Temperature
AJP	Average June Precipitation
AL	Aleutian Low
CPC	Climate Prediction Center
CRU	Climate Research Unit
DEP	Delta EP = January East Pacific Teleconnection index minus the April East Pacific Teleconnection index. This index measures changes in atmospheric circulation from winter to spring
EP	East Pacific: a teleconnection index used to quantify atmospheric circulation
GOA	Gulf Of Alaska
IPCC	Intergovernmental Panel on Climate Change
LFDB	Large Fire Data Base
MLR	Multiple Linear Regression
NOAA	National Oceanic and Atmospheric Administration
PDO	Pacific Decadal Oscillation
PDOWIN	Average PDO value for the months of January and February
WRCC	Western Region Climate Center

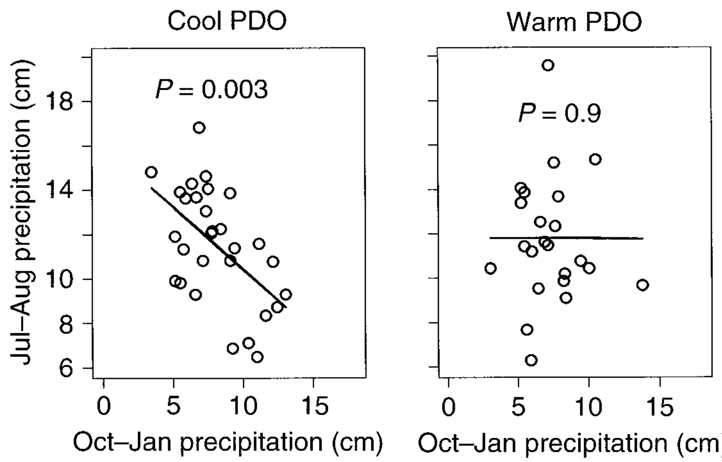

FIG. 8. Scatter plots of July–August precipitation vs. previous September–January precipitation. Plots are partitioned based on the sign of the average PDO values for the months of January and February (PDOWIN). The negative correlation between winter and summer precipitation exists only during cool phases of the PDO. Hence during cool phases of the PDO, it is less likely that a dry winter will be followed by a dry summer. The least-squares regression line and *P* value (corresponding to the test of slope equal to zero) are presented.

periods) yielded explanatory variables with comparatively lower explanatory capability. Hence, monthly temperatures exert differential impacts on the annual area burned.

The parameter estimate for AAT is negative, indicating that lower April temperatures are associated with greater area burned (Table 1), but the interpretation is made difficult by nonlinear interactions with DEP. When zonal flow is dominant in the spring (DEP > 0), April temperatures are positively correlated with area burned, whereas when meridional flow is building, April temperatures are negatively correlated with area burned. The reason for this shift is not fully understood, but is likely due to interactions with the precipitation signal associated with the EP. When zonal flow is dominant, precipitation is more likely, and higher April temperatures can signal the beginning of break-up and result in an earlier fire season. When meridional flow is dominant, precipitation is less likely and elevated April temperatures may result in snowmelt before the organic horizon is thawed enough to accept the meltwater as recharge. The impact of spring snowmelt on fire dynamics is a subject that requires further study.

Temperatures for the months of May, June, and July are positively correlated with area burned. May is the month when deciduous trees typically break dormancy in the Interior. In the period between snowmelt and leafout, deciduous stands can have greater flammability than conifers. This is partly because deciduous stands are more prevalent on south-facing slopes, and respond rapidly when warm, dry spring conditions exist. Elevated temperatures in May decrease available moisture for ground cover and increase progressive drying of deeper organic layers. Elevated May temperatures can be sufficient to develop convective thunderstorm activity, although the majority of lightning strikes in the Interior typically occur during June and July (Reap 1991). Average June and July temperatures probably exert their influence through drying of the organic layer and development of convective activity.

Precipitation.—As the sole precipitation variable in the regression model, average June precipitation (AJP) was the least significant among the other variables (Table 1). Depending on the thaw depth of the organic layer, June precipitation data can yield information regarding moisture status of organic layers. Temperature is also an integral component of moisture status, and in general, area-averaged anomalies of monthly temperature and precipitation are negatively correlated in high latitudes during summer. A common factor in anomalies of both variables is cloudiness, which is associated with lower temperatures and greater precipitation during summer. This correlation is primarily driven by the prevalence of frontal low-pressure systems that typically have large areas of cloud cover and relatively spatially homogenous precipitation. Alternatively, convective storms associated with surface heating can result in highly localized cloud cover and precipitation, which reduces the effectiveness of monthly precipitation as an explanatory variable.

Intramonthly variability of precipitation is also an important factor with respect to moisture status of the organic layer (Flannigan and Harrington 1988). A month receiving average precipitation that occurs on only several days can have a greater potential for fire than a month in which the same total rainfall is distributed evenly throughout the month. In general, months with more precipitation will also have greater intramonthly variability. This hinders attempts to determine the relative importance of total monthly precipitation vs. timing. The lack of information regarding intramonthly variability in precipitation is partly obviated by the use of the EP monthly indices, which implicitly contain information about circulation and the potential for blocking highs associated with reduced precipitation (Johnson and Wowchuk 1993, Skinner et al. 1999).

DISCUSSION

This analysis provides a framework for understanding the influence of ocean–atmosphere interaction on the fire regime of Interior Alaska. Our study is the first to build a statistical model quantifying the link between teleconnections, weather, and area burned in Interior Alaska. Intuitively one assumes that, in the short term, less precipitation and higher temperatures increase fire danger. This work extends such reasoning to the antecedent ocean–atmosphere interactions that influence short-term weather, and it quantifies the influences of these factors on the annual area burned. Teleconnections modify atmospheric circulation, and the statistically significant relationships between teleconnection indices and monthly weather provide plausible physical mechanisms for the teleconnections to influence area burned. The relationships between teleconnections, weather, and conditions that are favorable for large areas burned are considered below.

Teleconnection influences on weather

Positive phases of the EP teleconnection correspond with upper airflow that is meridional, whereas negative phases are associated with zonal circulation and strengthened westerlies in the eastern North Pacific. The meridional flow is conducive to the formation of blocking highs that impact short-term weather and fire behavior in Interior Alaska. Blocking highs typically persist for several days to several weeks, and influence the fire potential across regions of 100–1000 km (Johnson and Wowchuk 1993). In summer, surface-blocking high-pressure systems bring warm temperatures and low precipitation that can cause deep drying of the organic layer. Hence, midtropospheric anomalies and the surface high-pressure systems that accompany them increase fire danger at a landscape scale. Shifts from positive to negative EP indices in the spring (DEP $>$ 0) are associated with greater precipitation and cooler temperatures across Interior Alaska.

With respect to the EP teleconnection, the antecedent atmospheric circulation pattern most strongly correlated with a large area burned is a negative EP index in the winter that shifts to a positive EP index in the spring. To quantify this, DEP is defined as the January EP index minus the April EP index. DEP measures the change in atmospheric circulation from winter to spring. The negative value of the parameter estimate for DEP (Table 1) shows that a shift from a negative EP index in January to a positive EP index in April is correlated with greater area burned in the following summer. This shift represents a departure from the positive seasonal correlation that is characteristic of the autoregressive EP teleconnection (Fig. 4). As a consequence of the impact on atmospheric circulation, negative values of DEP are associated with drier than normal conditions for the months of March through August (Fig. 5) and increased temperatures for the months of May and June (Fig. 6). Shifts in the EP index from negative phases in winter to positive phases in spring modify atmospheric circulation and increase the likelihood of blocking ridges forming in the following summer. In general, warmer and dryer early summer conditions favor a progressive drying of deeper organic layers. As the length of a dry spell increases, there is greater potential for widespread, intense combustion due to increased homogeneity of favorable fuel conditions. In the boreal forest of Alaska, the majority of fires are dependent on combustion of the organic layer; however, during extreme fire events fires can burn in the canopy without consuming much soil organic matter. Hence DEP likely influences the number of hectares burned in Interior Alaska through its effects on moisture conditions in the organic layer. The cumulative impact of the warmer and drier summer conditions associated with negative values of DEP is a greater area burned (Table 2).

Like the EP teleconnection, the PDO also influences the number of hectares burned in interior Alaska through modification of weather. Of the PDO indices evaluated, the index comprising of the average for the winter months of January and February (PDOWIN) explains the greatest amount of variability in the MLR. Like the EP teleconnection, the PDO dictates certain aspects of atmospheric circulation. Specifically, ridging in the North Pacific is more frequent during cool phases of the PDO, whereas in the warm phase the development of troughs in this region is more likely (Bond and Harrison 2000). The PDOWIN index is positively correlated to late spring precipitation (Fig. 7) in Alaska.

The phase of the PDO also influences correlation between winter and summer precipitation amounts for Interior Alaska (Fig. 8). In the winter, there is a monotonic decrease in the average monthly precipitation from October to May, and the majority of winter precipitation comes in the months of October and November. Although the average temperature for October is below freezing, precipitation events during this month can contribute to moisture content at the soil surface. Impacts of the interaction between winter and summer precipitation on the area burned require further evaluation, but are possibly driven by soil moisture dynamics in the organic horizons. Specifically, differences in snowpack can potentially influence soil moisture in the following spring. For soils with organic horizons, the ability of snowmelt water to percolate into the active layer depends on the quantity of ice in soil pores (Kane 1980). Moisture content at the soil surface has been observed to increase throughout the winter, with this effect being most pronounced for wet soils. Hence, higher soil moisture contents correspond to greater amounts of ice present in the frozen soil, which in turn reduces the infiltration rate and the saturated hydraulic conductivity (Kane 1980). Similar results have been found for mineral soils in boreal forests (Zhao and Gray 1999). Additionally, after winters with little snowfall, it is possible for organic layers at high latitudes to remain frozen into July (Nyberg et al. 2001). Hence the importance of summer precipitation can depend on the development and persistence of winter snowpack. Wetter soils during freeze-up in the fall coupled with above-average precipitation during the winter can potentially result in drier soil organic layers in the following spring. Soil moisture of organic layers plays a critical role in the smoldering combustion of deeper organic horizons (Miyanishi and Johnson 2002). Fires that smolder in deeper organic horizons are more likely to persist through rainfall events that may occur. Although the correlation between winter and summer precipitation is significantly different between warm and cool phases of the PDO, none of the fall or winter monthly precipitation variables were significant in the regression. Hence if the relationship between the PDO and the correlation between winter and summer precipitation influences area burned in the subsequent year, the mechanism is likely complex and has yet to be definitively characterized.

The majority of summer precipitation in Alaska comes in the months of July and August, and during this time area-averaged anomalies of monthly temperature and precipitation are negatively correlated. As a consequence, elevated temperatures typically accompany low precipitation and both are conducive to increased area burned. During cool phases of the PDO, there is a strong negative correlation between cumulative precipitation amounts for October–November and July–August (Fig. 8). Hence in cool phases, dry winters are likely to be followed by wet summers and dry summers are likely preceded by relatively wet winters. Simply put, it is less likely to have both a wet winter and a wet summer during cool phases of the PDO than it is during warm phases of the PDO. Following the reasoning in the previous paragraph, the relationship between winter and summer precipitation during the cool phase of the PDO can potentially produce more favorable conditions for greater area burned, since wet winters are likely to be followed by dry summers (Fig. 8). Alternatively, during the warm phase of the PDO, there is negligible correlation between winter and summer precipitation (Fig. 8), and it is less likely that a warm summer will follow a wet winter. Shifts in sea-ice dynamics off the west coast of Alaska have been linked to changes in the phase of the PDO (Niebauer 1998) and it is possible that the shift in intra-annual correlation between precipitation signals is related to the impact of the PDO on sea-ice extent.

The Pacific Decadal Oscillation and the Aleutian Low

The phase of the PDO is positively correlated with spring precipitation (Fig. 7) in Alaska. One mechanism that can explain these short-term weather anomalies is impacts of the PDO on the location and intensity of the Aleutian Low (Niebauer 1998, Papineau 2001). In the period used for this study, there were only six times (1957–1958, 1969–1970, 1976–1977, 1990–1991, 1999–2000) where substantial (greater than a 1.6 unit shift in the PDOWIN metric for sequential years) shifts from cool to warm phase of the PDO occurred. One of the consequences of this type of shift was that the Aleutian Low intensified and moved southeast of its former position. This shift causes a more easterly (less southerly) flow component across Interior Alaska and is associated with regional summer droughts. The years of 1957, 1969, 1977, 1990, and 1999 had the first, fourth, fifth, second, and 12th largest fire years (respectively) of the period from 1950 to 2003. One of the most extreme cases of this was in the summer of 1977, when the Kotzebue weather station recorded 0.03 inches of total precipitation for the months of June and July; (*available online*).[11] Not surprisingly, many fires that burned that summer were located in the northwest part of the state near Kotzebue.

Model development

A key component of any model development lies in testing of the final model. This is especially important when developing a statistical model through the sequential elimination of explanatory variables based on significance tests. The potential always exists for the chance selection of statistically significant variables that are of little practical importance. By the definition of statistical significance, the probability of this happening increases as more potential explanatory variables are evaluated. A first step in exploring the potential for the selection of explanatory variables that are not practically significant is to consider plausible mechanisms for the selected variables to influence the response. All of the variables included in the regression model (Table 1) have plausible physical mechanisms for influencing annual area burned (Figs. 5–8, Table 2), and the identification of these variables will help guide future exploration of the link between climate and fire in different boreal systems.

Another potential issue is that of correlation between explanatory variables, or collinearity. When dealing with monthly temperature data, correlation between months should be expected, since months are somewhat arbitrary designations for discretizing the year. For example, a high-pressure ridge bringing warm and dry weather at the end of May will likely have a similar influence on the weather in the beginning of June. The collinearity that exists between explanatory variables can influence model output in several ways, including the selection of variables with little practical significance. A quantitative way to assess the impact of both collinearity and the potential for selection of variables with little practical significance is through cross-validation. If explanatory variables of little practical significance have been selected due to collinearity or chance, cross-validation routines often reveal this. Based on our cross-validation results, the impact of collinearity on model predictions seems negligible, and

[11] ⟨http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?akkotz⟩

there do not appear to be any variables selected that are not significant both practically and statistically.

Forecasting with the model

The results of this paper can be used for long-range (monthly-to-seasonal) forecasts of the magnitude (area burned) of the upcoming fire season. As an example, consider two forecasts for the upcoming 2004 fire season, one at the end of April and one at the end of May. Estimates of the other necessary monthly variables are obtained by interpreting the Climate Prediction Center prognostic discussion for long-lead seasonal outlooks (http://www.cpc.ncep.noaa.gov/products/predictions/90day/fxus05.html). Based on the prognostic discussions, the 60th percentile of the May, June, and July temperatures will be used for the first forecast (made at the end of April) and the 70th percentile will be used for the June and July temperature for the second forecast (made at the end of May). The median June precipitation will be used for first forecast and the 40th percentile will be used for the second. Based on this information, the first forecast (end of April) is for 41 000 ha and the second forecast (end of May) is for 135 000 ha. Both of these are well below average (270 000 ha). In fact, as of the end of July 2004, the total area burned had already reached roughly 1 780 000 ha (second overall since 1950). In Fairbanks, June 2004 was the second hottest in the past 100 years. In addition to the hot weather, lightning activity was record-breaking as well. On the 14th of June, 8589 lightning strikes were recorded throughout the state, and one month later, on July 15th, >9000 strikes were recorded (courtesy of the National Weather Service). These represent two of the largest single-day outbreaks on record for the state. With the values for June inserted in the statistical model (and using the 70th percentile for July temperature), the estimate is 2 100 000 ha burned. This exercise demonstrates the importance of June temperature in the statistical model. Attempts to use this model for planning should incorporate multiple plausible scenarios for June temperatures in order to appropriately plan for the upcoming season.

Conclusion

Climate, fire, and vegetation in the boreal forest of Interior Alaska interact on multiple spatial and temporal scales. It is clear from this work that teleconnections operating on multiple timescales influence the annual area burned across Interior Alaska. The results presented in this paper provide evidence linking the East Pacific teleconnection and the Pacific Decadal Oscillation to several weather variables that are directly related to the annual area burned in Interior Alaska. The most likely, ultimate mechanisms for these linkages are shifts in atmospheric circulation. Strong positive phases of the EP pattern are conducive to the development of blocking highs that impact short-term weather and fire behavior. Negative phases of the EP pattern are associated with strengthened westerlies in the Eastern North Pacific as a consequence of a more zonal upper airflow over the region south of Alaska. The shift in sign of the EP teleconnection over a period of several months in winter exerts a significant signal on both temperature and precipitation during the spring and summer in Interior Alaska.

The Pacific Decadal Oscillation exerts a direct influence on winter temperatures and summer precipitation and also modifies the correlation between winter and summer precipitation. During cool phases of the PDO, there is strong negative correlation between winter and summer precipitation. One possible explanation for the importance of above-average winter precipitation is that decreased percolation due to ice in the soil pores can potentially leave the organic layers more susceptible to warm, dry temperatures in May and June. This scenario is more likely during cool phases of the PDO, and consequently 69% of the area burned for the period of this study occurred when the PDOWIN metric was <0 (i.e., cool phases of the PDO). The interaction between moisture content of the soil organic layers, winter precipitation, and fire extent in the following year remains unclear and merits further study.

This work represents a first step in quantifying the link between weather and fire in Alaska. The multiple linear regression model used to characterize this link is a simple tool for taking this first step. The model lacks a spatially explicit component, as monthly temperatures and precipitation represent averages from a relatively small number of sites located throughout the Alaskan Interior. The use of broader circulation indices reduces the reliance on, and possible concerns about, the representativeness of local (single-point) surface-based measurements made in a heterogeneous landscape. The interactions between weather and fire characterized in this work were developed conditional on the current spatial distribution of vegetation across Interior Alaska. Debate exists as to the importance of age-dependent flammability in the boreal forest (Johnson 1992, Johnson et al. 1998, 2001, Hely et al. 2000*a*, *b*, Ward et al. 2001). If stand flammability does indeed change as a function of age, the spatial distribution of such vegetation would mediate the relationship between climate and fire. Cross-validation of the model suggests that collinearity and spurious variable selection are not serious issues and model predictions can provide input to fire management officials charged with developing resource allocation plans for upcoming fire seasons. Due to the strong dependence of area burned on weather, forecasts of area burned produced by the model are only as reliable as the forecasts for temperature and precipitation used in the model. Specifically, June temperature plays a critical role in the magnitude of area burned. Future attempts to forecast area burned in Alaska should focus on identifying those atmospheric mechanisms that most strongly influence June temperature. A next step is to apply similar MLR procedures for tundra vs. forest vegetation to identify the climatological characteristics that drive the burning of different vegetation types.

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