Tundra burning in Alaska: Linkages to climatic change and sea ice retreat

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[1] Recent climatic warming has resulted in pronounced environmental changes in the Arctic, including shrub cover expansion and sea ice shrinkage. These changes foreshadow more dramatic impacts that will occur if the warming trend continues. Among the major challenges in anticipating these impacts are "surprises" stemming from changes in system components that have remained relatively stable in the historic record. Tundra burning is potentially one such component. Here we report paleoecological evidence showing that recent tundra burning is unprecedented in the central Alaskan Arctic within the last 5000 years. Analysis of lake sediment cores reveals peak values of charcoal accumulation corresponding to the Anaktuvuk River Fire in 2007, with no evidence of other fire events throughout the past five millennia in that area. Atmospheric reanalysis suggests that the fire was favored by exceptionally warm and dry weather conditions in summer and early autumn. Boosted regression tree modeling shows that such conditions also explain 95% of the interannual variability in tundra area burned throughout Alaska over the past 60 years and that the response of tundra burning to climatic warming is nonlinear. These results contribute to an emerging body of evidence suggesting that tundra ecosystems can burn more frequently under suitable climatic and fuel conditions. The Anaktuvuk River Fire coincides with extreme sea ice retreat, and tundra area burned in Alaska is moderately correlated with sea ice extent from 1979 to 2009 ($r = -0.43$, $p = 0.02$). Recurrences of large tundra fires as a result of sea ice disappearance may represent a novel manifestation of coupled marine-terrestrial responses to climatic warming.

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1. Introduction

[2] Climatic change over the past several decades has caused a dramatic increase in the frequency of large wildfires in many regions [*Bowman et al.*, 2009; *Kasischke and Turetsky*, 2006; *Westerling et al.*, 2006], highlighting the need to understand climate-fire linkages and their environmental and socioeconomic impacts. Although numerous recent investigations have elucidated these linkages [*Duffy et al.*, 2005; *Marlon et al.*, 2008; *Parisien and Moritz*, 2009; *Westerling et al.*, 2006], little attention has been paid to fires in Arctic tundra ecosystems. At the biome scale, a defining feature of modern arctic tundra is that fires are rare and small in size [*Aber and Melillo*, 2001; *Wein*, 1976]. However, several studies provide evidence for tundra burning under suitable climate and fuel conditions [*Racine et al.*, 1985; *Higuera et al.*, 2008; *Jones et al.*, 2009].

[3] A striking example of tundra burning is the 2007 Anaktuvuk River Fire, an unusually large fire in the tundra of the Alaskan Arctic. This fire burned 1039 km^2 of the tundra on Alaska's North Slope, doubling the area burned north of 68°N in that region since record keeping began in 1950 (Figures 1 and 2b). The burn severity of the Anaktuvuk River Fire, as measured by the depth of soil organic matter consumed during the fire, was greater than typical tundra fires [*Jones et al.*, 2009]. In addition, much of the burn occurred in September, instead of during early and mid-summer, as with the majority of the Alaskan tundra fires over the past 50 years [*Racine et al.*, 1985], and the fire continued until snow blanketed the area in early October. These characteristics suggest that the Anaktuvuk River Fire represents a novel expression of ongoing arctic system

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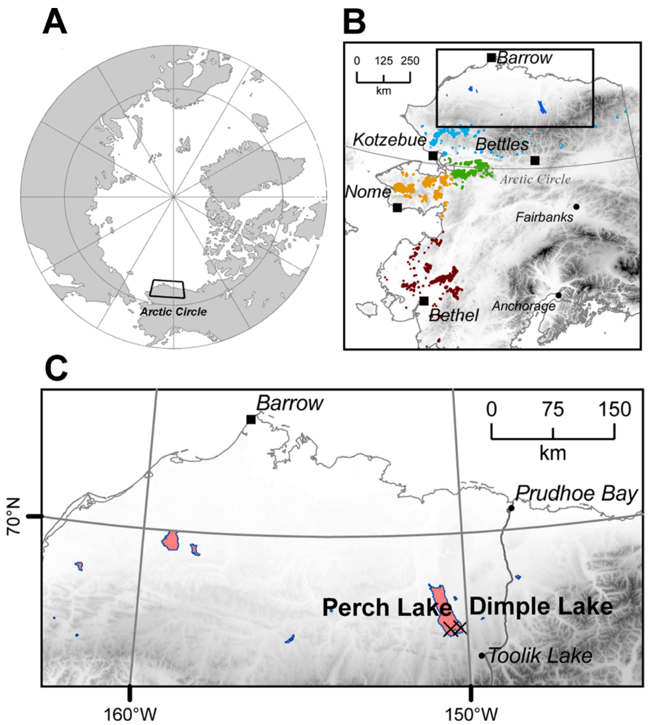

Figure 1. Locations of the Anaktuvuk River Fire, study sites for paleo fire reconstructions, and modern climate and area burned data sets. (a) North Slope of Alaska in a global context. (b) Area burned (colored polygons) in Alaskan tundra, as defined by the Circumpolar Arctic Vegetation Map [*Walker et al.,* 2005], from CE 1950–2009. Different-colored polygons identify tundra area burned in different ecoregions, from north to south: North Slope, Noatak and Brooks Range, Kobuk Valley, Seward Peninsula, and southwestern Alaska (see also Figure S2). Black squares indicate the five climate stations used for the climate-fire analysis. (c) Location of Perch and Dimple lakes (crosses) within the Anaktuvuk River Fire, with area burned as in Figure 1b.

changes associated with climatic warming. This possibility has far-reaching implications. For example, it has been speculated that tundra burning can play a significant role in the soil carbon budget [*Racine et al.*, 1985, 1987; *Wookey et al.*, 2009]. Tundra burning can also diminish foraging habitats for caribou [*Jandt et al.*, 2008], a key subsistence resource for arctic indigenous peoples.

[4] The objectives of our study are to evaluate the uniqueness of the Anaktuvuk River Fire and to examine potential climatic controls of this event as well as Alaskan tundra fires from CE 1950–2009. The first objective requires knowledge about the nature of tundra fire regimes from decadal to millennial timescales. Are large burns like the Anaktuvuk River Fire simply low-probability events that occur every several centuries, or is the Anaktuvuk River Fire truly novel in the context of the past several millennia? Charcoal analysis of lake sediment offers the only means to answer such questions [*Gavin et al.*, 2007]. We obtained sediment cores from Perch (68.94°N, 150.50°W) and Dimple (68.95°N, 150.20°W) lakes, both located within the Anaktuvuk River Fire. These cores were analyzed for charcoal particles to infer fire history over the past five millennia. To address the second objective, we used atmospheric reanalysis to assess climatic conditions under which the Anaktuvuk River Fire occurred, and we corroborated our interpretations of the Anaktuvuk site at broader spatial scales by modeling interannual variability in area burned in Alaskan tundra as a function of summer climatic conditions. In addition, we explored the possible linkages among climatic anomalies, the Anaktuvuk River Fire, and Arctic sea ice retreat. These results have potential implications about mechanisms controlling tundra burning across broader arctic regions.

2. Materials and Methods

2.1. Lake Sediment and Charcoal Analyses

[5] Perch and Dimple lakes have maximum depths of 12.6 and 8.0 m and surface areas of 14 and 10 ha, respectively. Perch Lake was surrounded by more continuous burned area than Dimple Lake. In August 2008, we obtained a sediment core from the deepest area of each lake (89.5 and 104.0 cm long for Perch and Dimple, respectively) using a polycarbonate tube fitted with a piston and attached to coring rods. An intact sediment water interface was preserved during the retrieval of both cores. The Perch and Dimple sediments are nonlaminated and finely laminated gyttja, respectively. The upper 10 cm of each core was sliced at 0.5 cm intervals in the field, and deeper sediments were split longitudinally and sliced at 0.25 cm intervals in the laboratory.

[6] We developed a chronology for each core on the basis of ^{210}Pb dates [*Binford*, 1990] of bulk sediments for the upper 7–17 cm and accelerator mass spectrometry ^{14}C dates of terrestrial macrofossils from deeper sediments (see Data Set S1).[1] The ^{14}C ages were calibrated using CALIB 5.0 and the IntCal 04 data set [*Reimer et al.*, 2004]. Age models were developed using a weighted cubic smoothing spline for both cores [*Higuera et al.*, 2009]. No lithologic evidence of a depositional hiatus exists in either core that may compromise our age models.

[7] Charcoal abundance was quantified in 3 cm^3 subsamples from contiguous 0.25–0.50 cm intervals, following *Higuera et al.* [2009] except for using a 180 μm sieve. The median sample resolutions are 16 and 3 years for the charcoal records from Perch and Dimple lakes, respectively. Our interpretation of only one fire occurring at each lake is also consistent with peak analysis done using the program CharAnalysis [*Higuera et al.*, 2009].

2.2. Analysis of Historic Tundra Fire-Climate Relations

[8] To evaluate whether the climatic drivers of the Anaktuvuk River Fire are consistent with climatic influences on fire across broader areas of Alaskan tundra, we constructed generalized boosting models (GBM) [*De'ath*, 2007; *Elith et al.*, 2008; *Friedman*, 2002] using the GBM function from the GBM package [*Ridgeway*, 2007] in R [*R Development Core Team*, 2008]. A model was used to estimate annual tundra area burned in Alaska as a function of June–September

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/jg/2009jg001270. Other auxiliary material files are in the HTML.

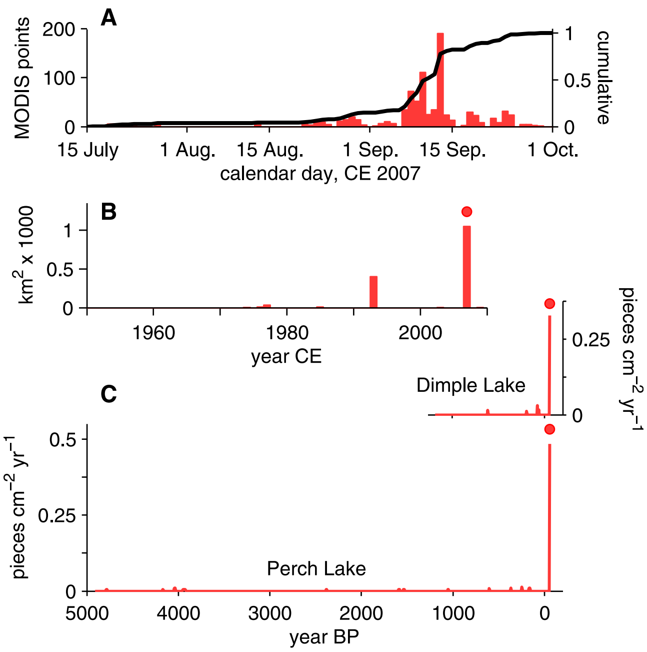

Figure 2. Fire history at three temporal scales. (a) Daily fire growth of the Anaktuvuk River Fire during the summer and fall of 2007, as number of 1 km^2 MODIS pixels. The majority of area burned in early to mid-September. (b) Annual area burned in Alaska north of 68°N from CE 1950–2009. (c) Millennial-scale fire history inferred from charcoal accumulation rates in the sediments of Perch and Dimple lakes ("B.P." is before CE 1950). Red dots in both Figures 2b and 2c denote CE 2007 and the Anaktuvuk River Fire.

mean temperature and precipitation. For annual area burned, we used the Alaskan wildland fire data set, which documents fires since 1950 (Available from Alaska Interagency Coordination Center at http://fire.ak.blm.gov/predsvcs/maps.php) [*Kasischke et al.*, 2002]. Tundra fires were defined as area burned in the Alaskan wildland fire data set that overlapped with tundra vegetation in the Circumpolar Arctic Vegetation Map (Figure 1b) [*Walker et al.*, 2005]. The explanatory variables of temperature and precipitation were computed by averaging the monthly average June–September (JJAS) station data from 1950 to 2009 from Barrow, Bethel, Bettles, Kotzebue, and Nome (Available from Western Region Climate Center at http://www.wrcc.dri.edu/summary/Climsmak.html). The spatial domains of these tundra fire and climate data sets are somewhat mismatched, which is inevitable because of the limited number of weather stations providing historic climate data from Alaska. However, summer climate, and in particular the atmospheric conditions associated with fire weather, develops from large-scale atmospheric circulation patterns that affect broad regions across Alaska [e.g., *Mock et al.*, 1998; *Duffy et al.*, 2005]. For example, mean JJAS temperatures are well correlated between the five weather stations used here ($0.38 < r < 0.77$; Figure S1), as well as with the temperature for the Anaktuvuk River Fire grid cell ($0.37 < r < 0.58$; Figure S1). Thus, climatic conditions conducive to fire occurrence in one region of Alaska are often associated with similar conditions in other regions of the state, making it appropriate to characterize climate at large spatial scales. This does not imply that all tundra areas in the state would burn in years when conditions are conducive to fire across large spatial scales because fire occurrence and spread depend on a variety of local factors such as ignitions and landform configurations.

[9] Model construction involved two steps. First, 1000 models were fit with subsets of the entire data set. For each model, 5 randomly selected years were removed, and a model linking area burned and climate variables was fit using the remaining data. Area burned estimates were then generated for each of the 5 randomly removed years. This resulted in a distribution of approximately $5 \times 1000/60 = 83$ estimates for each year. The median area burned for each year was regressed on observed area burned, and the other metaparameters for the GBM function were selected by optimizing the r^2 value from this regression. The number of regression trees is an important metaparameter for the GBM function, and for each of the 1000 models, this was computed using the "test" method with the training fraction set to 0.99. The second step was to fit a deterministic GBM of the annual area burned as a function of summer temperature and precipitation. This was done by setting the bag fraction parameter to 1.0 and using the average number of trees from the 1000 models generated in the first step.

2.3. Moderate Resolution Imaging Spectroradiometer-Derived Fire Growth

[10] The seasonal chronology of the Anaktuvuk River Fire (Figure 2a) is based on data from the MODIS Active Fire Mapping Program, maintained by the U.S. Forest Service Remote Sensing Applications Center (http://activefiremaps.fs.fed.us/gisdata.php?area=ak). This data set uses the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard satellites to identify thermally active areas ("hot spots") at 1 km^2 resolution and on daily timescales [*Giglio et al.*, 2006]. Cloud cover, low-intensity burning, and/or fires smaller than the 1 km^2 resolution can preclude fire detection, and thus the data set reflects an approximation of total fire size and fire growth. The MODIS-derived data set captured 83% of the total burned area in the Anaktuvuk River Fire (860 of 1039 km^2).

2.4. Atmospheric Reanalysis and Sea Ice Data

[11] The placement of the 2007 temperature and moisture anomalies near the Anaktuvuk River Fire into the context of 62 years of climate variations (1948–2009) utilized atmospheric reanalysis data from the National Centers for Environmental Prediction [*Kalnay et al.*, 1996]. A reanalysis synthesizes (and extends to a regular grid of points) available observations by assimilating the observations into an atmospheric model at regular (6 h) intervals. The resolution of the archived output is 2.5° latitude × 2.5° longitude. For this study, the reanalysis fields are surface air temperature, precipitation, and evapotranspiration. Precipitation is computed by the atmospheric model (utilizing the assimilated variables of temperature and humidity), and evapotranspiration is computed by a parameterization of the latent heat flux at the surface. The time series of temperature and precipitation (Figure 3) are for the June–September period

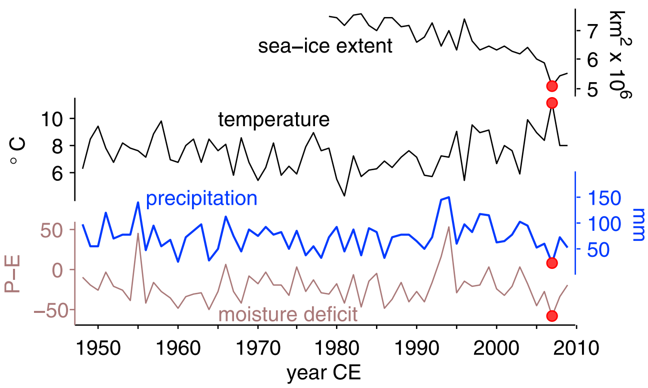

Figure 3. Northern Hemisphere sea ice extent and climatic conditions in the Anaktuvuk River Fire area. Climatic variables include temperature, precipitation, and moisture deficit (precipitation minus evapotranspiration). All curves show the annual June–September mean, and red dots denote the record-setting year of 2007.

of each year, 1948–2009, in the reanalysis grid cell containing the Anaktuvuk River Fire.

[12] The sea ice time series (Figure 3) shows the June–September mean ice extent anomaly for each year based on the satellite passive microwave measurements. The data were obtained from the National Snow and Ice Data Center (http://nsidc.org/).

3. Results and Discussion

[13] In this section, we report our fire reconstructions using sediment charcoal data and evaluate climate-fire relationships using historic records (CE 1950–2009). We then discuss the implications of summer sea ice reduction and associated climatic feedbacks for the future fire regimes of arctic tundra ecosystems. We emphasize that our discussion about the linkages of sea ice extent and tundra burning over the past few decades is speculative but that these linkages will probably become increasingly important during the 21st century with the projected rapid sea ice loss and accelerated land warming in the Arctic [*Lawrence et al.*, 2008].

3.1. Paleorecord of Tundra Burning

[14] At Perch Lake, all ^{14}C dates are in chronological order. At Dimple Lake, three of the ^{14}C ages (5825 B.P. at 55.75–56.25, 10,850 B.P. at 90.75–91.00, and 10,220 B.P. at 98.50–99.00 cm) most likely represent deposition of wood that had resided in tundra soils for several millennia, as inferred from the basal ^{14}C age of 1220 B.P. at 101–102 cm and the younger ^{14}C ages at several other stratigraphic positions from the same core. This problem is common in ^{14}C dating of arctic lake sediment cores [*Oswald et al.*, 2005]. We excluded these anomalously old dates and developed a chronology for each core using a series of ^{210}Pb and the remaining ^{14}C dates. On the basis of these models, the cores span the past ~5000 years at Perch Lake and ~1200 years at Dimple Lake (Data Set S1).

[15] Charcoal accumulation rates in the sediments that encompass the deposition of charcoal from the Anaktuvuk River Fire are 0.48 and 0.33 pieces cm^{-2} yr^{-1} at Perch and Dimple lakes, respectively (Figure 2c). In contrast to these prominent peaks, charcoal is either absent or occurs in trace amounts (representing distant fires) in the sediments prior to 2007 at both sites. This sharp contrast indicates that our fire reconstructions are insensitive to the nature of the age models. These results provide unambiguous evidence that the Anaktuvuk River Fire is unprecedented in this area over the past five millennia.

[16] A rigorous assessment of whether the Anaktuvuk River Fire was related to unprecedented climatic conditions requires paleoclimate records of the past 5000 years (period of the charcoal record). No such records exist from the Anaktuvuk River area. However, recent paleoclimate studies in other areas of Alaska offer compelling evidence that the past several decades were among the warmest and driest of the past eight millennia [*Clegg and Hu*, 2010; *Hu et al.*, 2001]. Along with evidence that the summer and autumn of 2007 were the warmest and driest of the past several decades in the area of Anaktuvuk River Fire (see below), existing paleoclimate records suggest the possibility that the climatic conditions associated with the fire were also exceptional in the context of the past five millennia.

[17] Although large fires are rare across the modern tundra biome, a number of tundra fires, including one as large as the Anaktuvuk River Fire, have occurred over the past 60 years in western Alaska (Figure 1b) [*Racine et al.*, 1985], where average summer temperatures are substantially higher than on the central Arctic foothills of Alaska. In addition, the total amount of tundra area burned across the state of Alaska was not the highest in 2007; record-high tundra burning occurred in 1977 under exceptionally warm and dry anomalies in northwestern Alaska (Figures 4a and S2). Furthermore, recent charcoal analyses of late glacial sediments from interior Alaska [*Higuera et al.*, 2008; *Tinner et al.*, 2006] suggest that tundra fire frequencies were as high as those of the modern boreal forests, when the regional climate was drier and shrub cover presumably more extensive than today. We do not know the size, seasonality, or severity of these late glacial tundra fires and cannot assess the uniqueness of the Anaktuvuk River Fire in these aspects using the paleorecord. Nonetheless, these late glacial records along with the Anaktuvuk River Fire and historic fires demonstrate that tundra ecosystems can burn frequently under suitable climatic and vegetation/fuel conditions.

3.2. Historic Record of Tundra Climate-Fire Relations

[18] The Anaktuvuk River Fire occurred under unusually warm and dry summer and early autumn conditions. Atmospheric analysis shows that in the area of the Anaktuvuk River Fire, the mean June–September temperature of 11.1°C was 3.7°C above the 1948–2009 mean (7.4°C) and 1.3°C above the previous maximum (9.8°C) set in 2004 (Figure 3). The reanalysis-derived moisture deficit (precipitation minus evapotranspiration or P–E) of −57 mm far exceeded the mean moisture deficit (−21 mm) and the previous record (−49 mm) in 1964. While the anomaly of precipitation was itself strongly negative in 2007, it was the combination of low precipitation and an excess of evaporation (driven by the warmth) that gave 2007 the most extreme moisture deficit of the past 61 years. Thus, the extent and severity of the Anaktuvuk River Fire likely resulted from exceptionally warm conditions coupled with seasonal drought in the area

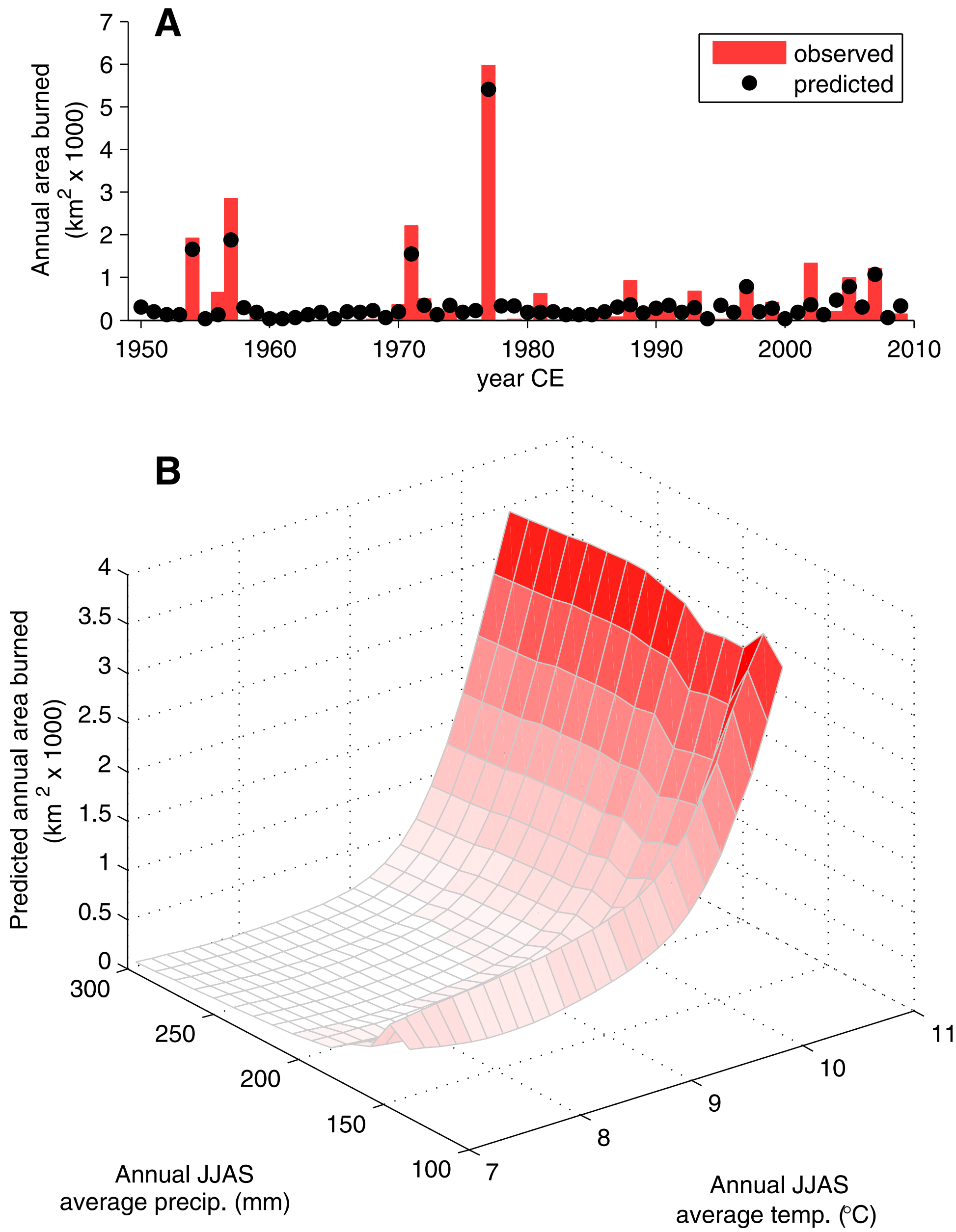

Figure 4. Tundra fire-climate relations in Alaska based on a generalized boosting model. The model explains 95% of the interannual variability in area burned in Alaskan tundra from CE 1950–2009. Tundra fires were defined as all area burned that overlapped with tundra vegetation on the Circumpolar Arctic Vegetation Map [*Walker et al.*, 2005]. The explanatory climate variables are annual average June, July, August, and September (JJAS) temperature and precipitation, calculated from the five locations identified in Figure 1. (a) Observed versus model-predicted area burned. (b) Smoothed response surface relating annual summer temperature and precipitation to tundra area burned.

of the burn. This interpretation is consistent with a recent analysis linking the Anaktuvuk River Fire with regional weather patterns [*Jones et al.*, 2009].

[19] Comparison of climate and tundra fire data from throughout the Alaskan Arctic and sub-Arctic also reveals strong climate-fire linkages over the past 60 years. In the generalized boosting model, June–September temperature and precipitation alone explain 95% of the interannual variability in observed area burned in Alaskan tundra (Table 1 and Figure 4a). June–August climate dominates this relationship, and unlike for the Anaktuvuk River Fire, September climate is only weakly correlated with tundra area burned in the past several decades. Furthermore, temperature is the more important variable in this model and has a nonlinear relationship with area burned (Figure 4b). A threshold response of area burned occurs when average summer temperature at the five weather stations (Barrow, Bethel, Bettles, Kotzebue, and Nome) exceeds approximately 9.5°C (Figure 4). This threshold is apparent at all precipitation levels. In our model, the effects of JJAS precipitation on

Table 1. Coefficient of Determination (r^2) for Generalized Boosting Models Relating Mean Annual June–September Temperature and Precipitation to Tundra Area Burned[a]

	Composite Climate Record	
Tundra Ecoregion	Barrow, Bethel, Bettles, Nome, Kotzebue	Bettles, Nome, Kotzebue
All	0.95	0.94
North Slope, Noatak	0.98	-
North Slope, Noatak, Brooks Range, Kobuk	0.93	-
Seward	0.99	-
Seward, southwestern Alaska	0.93	-
Southwestern Alaska	0.92	-

[a]The full model, predicting area burned across all ecoregions, was developed using composite climate records based on two different sets of climate stations. The five-station composite climate record was also used to predict tundra area burned within individual tundra ecoregions.

tundra area burned is less pronounced and more complex than those of JJAS temperature, probably because of the greater spatial heterogeneity in precipitation across various tundra regions. The Anaktuvuk River Fire occurred under conditions that crossed the temperature threshold for the occurrence of large tundra fires: in 2007 average June–September temperature at the five weather stations was 10.6°C, the highest in the 60 year record. Precipitation was not as extreme statewide; at 208 mm, it was only slightly below the series average of 216 mm. The mechanism by which warm conditions promote large fires is by decreasing fuel moisture content, which in turn increases the probability of fire ignition and spread [*Rothermel*, 1972].

[20] Over the past 60 years, fires have occurred in all major tundra regions across Alaska (Figure 1). Despite the strong spatial correlations of summer temperature across these regions, climatic conditions differ substantially among them (e.g., the mean JJAS temperature is 2.22°C and 10.77°C at Barrow and Bethel, respectively). The temporal pattern of tundra area burned also varies somewhat among regions (Figure S2), reflecting variations in climate, in tundra vegetation, and in the stochasticity of lightning ignition. However, our results indicating that summer temperature and precipitation are the major drivers of tundra area burned (Figure 4) are robust to similar analyses at smaller spatial scales. Specifically, generalized boosting models using climate data from the same five weather stations explain 92%–99% of the variability in annual area burned in the individual tundra regions (Figure 1 and Table 1). This robustness indicates that tundra fires respond to the same climatic variables across Alaska, regardless of the underlying variability in vegetation, in topography, or in climatology.

3.3. Possible Linkages of Tundra Burning and Sea Ice Retreat

[21] One of most striking manifestations of ongoing global change is the rapid retreat of Arctic sea ice [*Stroeve et al.*, 2008]. Annual tundra area burned in Alaska is moderately correlated with sea ice extent from 1979 to 2009, the period of overlap between the two records (Spearman rank correlation, $r_s = -0.43$; $p_{auto} = 0.02$, accounting for temporal auto correlation in each series; Figure 5). Furthermore, since 1979 the 3 years with the highest values of annual tundra area burned in Alaska all occurred within the most recent 7 years, during which sea ice cover displayed a dramatic decreasing trend (Figure 5). However, the relationship of tundra burning and sea ice is not straightforward, as indicated by the moderate correlation from 1979 to 2009 and by large areas of tundra burning prior to 1979 (i.e., 1954, 1957, 1971, and 1977), when the sea ice cover was presumably more extensive. This complexity results partially from differences in climatic sensitivity to changes in sea ice extent among different tundra regions. For example, summer temperatures in the tundra areas of Alaska's North Slope are most likely regulated by sea ice extent, whereas summer temperatures in the tundra areas of western Alaska are controlled by weather fronts off of the Bering Sea, which has been ice free during the summer over the past 30 years. Indeed JJAS temperature at Barrow is significantly correlated with the sea ice extent ($r_s = -0.44$, $p_{auto} = 0.034$) but JJAS temperature at Nome is not ($r_s = 0.02$, $p_{auto} = 0.466$). However, model simulations suggest that extensive sea ice loss during the 21st century will lead to increased temperatures throughout much of the Arctic and beyond [*Lawrence et al.*, 2008]. We speculate that over the past several decades, sea ice retreat has become increasingly important in facilitating warm summers and extending the fire season in tundra ecosystems.

[22] The Anaktuvuk River Fire may be an extreme example of this effect, illustrating some of the processes linking sea ice extent and tundra burning. During the summer of the Anaktuvuk River Fire, sea ice cover underwent its most extreme retreat since the 1970s (Figure 3) and probably much longer. This retreat may have affected temperatures in the Anaktuvuk River area, as sea ice extent and air temperature time series for the Anaktuvuk River region (Figure 3) are significantly correlated ($r = -0.64$, $p_{auto} = 0.017$). Sea ice loss should have a particularly pronounced warming effect during the late summer and fall, when summer heat absorbed by open water is released into the atmosphere [*Lawrence et al.*, 2008]. The timing of the Anaktuvuk River Fire spread is consistent with this scenario, as the fire began in mid-July but remained small until

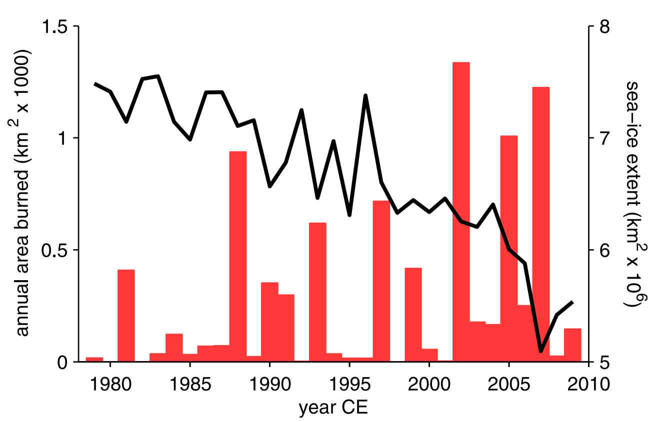

Figure 5. Comparison of Northern Hemisphere sea ice extent (as in Figure 3) and tundra area burned in Alaska (as defined in Figure 4a from CE 1979–2009, the period of overlap between the two records).

early September, when it spread more rapidly (Figure 2a) [*Jones et al.*, 2009]. Further, extensive sea ice retreat and associated late freezeup should favor a late onset of snow cover, which ultimately extinguished the Anaktuvuk River Fire. Thus, the extreme sea ice reduction in 2007 is a plausible explanation for the late season timing of the Anaktuvuk River Fire.

[23] Alternatively, the correlation of sea ice extent and air temperature may reflect the possibility that they both responded to variation in wind strengths and directions related to large-scale circulation anomalies. Although such anomalies may have a tendency to result in the cooccurrence of large tundra fires with sea ice retreat and its climatic feedbacks, this possibility renders uncertainty in directly attributing the tundra burning to the extreme sea ice retreat in the summer of 2007. For example, the frequency of lightning strikes and hence possible fire ignitions appear to have increased dramatically on the North Slope of Alaska over the past several decades (Data available from Alaska Interagency Coordination Center at http:/fire.ak.blm.gov). Nonclimatic conditions, such as increased abundance and density of tundra shrubs [*Chapin et al.*, 2005; *Tape et al.*, 2006; *Higuera et al.*, 2008], may also have set the stage for the unprecedented extent and severity of the Anaktuvuk River Fire.

3.4. Implications of Changing Climate and Increased Tundra Burning

[24] Despite the complexity of diagnosing the causes of the Anaktuvuk River Fire, our analyses clearly demonstrate that tundra burning was strongly linked to temperature and moderately linked to precipitation in both 2007 and over the past 60 years and that a temperature threshold exists, which, if crossed, could result in tundra burning that far exceeds rates witnessed in the recent past. Given these relationships, the ongoing acceleration in loss of sea ice [*Stroeve et al.*, 2008] and projected climatic feedbacks [*Lawrence et al.*, 2008; *Serreze et al.*, 2009] raise major concerns about future shifts in tundra fire regimes. The most reliable climate models predict that summer ice will vanish in the Arctic Ocean within 30 years [*Wang and Overland*, 2009]. The amplification of climatic warming throughout the land areas of the Arctic [*Lawrence et al.*, 2008] has the potential to dramatically increase tundra burns similar to the Anaktuvuk River Fire. Such late season fires burn deeper and more intensely than early season fires because the greater permafrost thaw depths and drier organic matter of tundra soils facilitate burning. Climatic warming associated with sea ice declines are also expected to cause rapid permafrost degradation [*Jorgenson et al.*, 2006; *Lawrence et al.*, 2008], and tundra fires themselves would further increase permafrost thaw depths [*Fetcher et al.*, 1984; *Racine et al.*, 1987; *Wein*, 1976]. Permafrost thawing may enhance drainage in upland tundra ecosystems, thereby decreasing soil moisture and further exacerbating the vulnerability of tundra ecosystems to late season fires. Furthermore, the continued increase in shrubs due to climatic warming [*Chapin et al.*, 2005; *Tape et al.*, 2006] should play an increasingly important role in tundra burning [*Higuera et al.*, 2008]. Together these factors will likely increase the risk of large fire events in the tundra biome within the next several decades, a pattern that has been predicted to occur in other biomes [*Fischlin et al.*, 2007].

[25] Recent studies demonstrated direct biological and physical impacts of tundra fires on arctic terrestrial ecosystems [*Jandt et al.*, 2008; *Liljedahl et al.*, 2007]. An increase in the frequency and extent of extreme tundra fires may alter land-atmosphere feedbacks, with large-scale and long-lasting ramifications [*Sitch et al.*, 2007]. In particular, the rarity of large, severe fires in the tundra biome has been an important factor contributing to the role of tundra ecosystems as a major carbon sink over geological history [*Sitch et al.*, 2007; *Zimov et al.*, 2006]. Increased tundra burning and associated releases of soil carbon may change the role of tundra ecosystems in the global carbon cycle, although we cannot quantify such effects within the scope of this study. Improving our understanding of tundra fire regime responses to climatic change associated with sea ice reduction is necessary for projecting Earth system dynamics, developing ecosystem management strategies, and preparing arctic residents for future changes.

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