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Fire Behavior, Weather, and Burn Severity of the 2007 Anaktuvuk River Tundra Fire, North Slope, Alaska

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Abstract

In 2007, the Anaktuvuk River Fire (ARF) became the largest recorded tundra fire on the North Slope of Alaska. The ARF burned for nearly three months, consuming more than 100,000 ha. At its peak in early September, the ARF burned at a rate of 7000 ha d^{-1}. The conditions potentially responsible for this large tundra fire include modeled record high summer temperature and record low summer precipitation, a late-season high-pressure system located over the Beaufort Sea, extremely dry soil conditions throughout the summer, and sustained southerly winds during the period of vegetation senescence. Burn severity mapping revealed that more than 80% of the ARF burned at moderate to extreme severity, while the nearby Kuparuk River Fire remained small and burned at predominantly (80%) low severity. While this study provides information that may aid in the prediction of future large tundra fires in northern Alaska, the fact that three other tundra fires that occurred in 2007 combined to burn less than 1000 ha suggests site specific complexities associated with tundra fires on the North Slope, which may hamper the development of tundra fire forecasting models.

Introduction

Throughout the Holocene fire has played a major role in ecosystem processes in Alaska (Chapin et al., 2006). However, there is new evidence that wildfires in Alaska are increasing in frequency, severity, and duration (Chapin et al., 2008; Kasischke and Turetsky, 2006). During the 2004 and 2005 fire seasons, 4.5 million hectares of boreal forest burned, comprising about 10% of the estimated boreal forest in Alaska, while 2007 showcased the largest and longest burning tundra fire on record on the North Slope of Alaska (Racine and Jandt, 2008). Further, a recent study highlights the past importance of fires in the tundra ecosystem and suggests increased tundra fire frequency in the 21st century (Higuera et al., 2008), in response to observed and predicted increases in shrub abundance in the Arctic (Sturm et al., 2001; Tape et al., 2006). These recent events contribute to the growing recognition of the role fire may play in ecosystem change with a warming climate (Rupp et al., 2000).

Although the potential for an increase in tundra fires is recognized, relatively little is known of the long-term effects and cycling of such events. Studies conducted on tundra fires to date have focused on short term changes in the composition and structure of tundra vegetation communities within the burn area, which may have important implications for carbon storage, surface energy balance, winter snow-depth, and forage for herbivores (Jandt et al., 2008). Vascular plants quickly recover to pre-fire levels, regaining pre-burn primary production and biomass within 10 years (Wein and Bliss, 1973; Racine et al., 2004). Much of the early recovery is due to vigorous regrowth of sedges, as the tussock growth form is particularly resistant to fire mortality. Dwarf shrubs like *Ledum palustre* and *Betula nana* resprout readily from rhizomes. Lichen species important as winter caribou forage take much longer to recover after disturbance (Jandt et al., 2008), and the influence of confounding factors such as climate warming upon recovery timelines is unknown. Further, it has been hypothesized that late season tundra fire activity may have the ability to remove more surface-soil organic matter and kill more plant parts, prolonging grass, sedge, and shrub plant regeneration in subsequent years (Wein, 1976).

Tundra fires also have implications to permafrost conditions. Tundra fires may remove all or some of the insulating organic soil layer, lower surface albedo, increase soil moisture, and create conditions conducive to a longer thaw period, which result in initially deeper thaw of the active layer following the burn and possibly thaw settlement (MacKay, 1995; Liljedahl et al., 2007). In the zone of continuous permafrost or flat terrain within discontinuous permafrost, thaw depths generally return to pre-fire levels within 10 to 25 years (MacKay, 1995; Racine et al., 2004), however along hillslopes in the discontinuous permafrost zone fire can lead to complete degradation of permafrost (Racine et al., 2004).

The Anaktuvuk River fire (ARF), located within the zone of continuous permafrost, burned from 16 July until early October 2007, making it the largest and longest burning recorded tundra fire on the North Slope of Alaska and the largest recorded fire in

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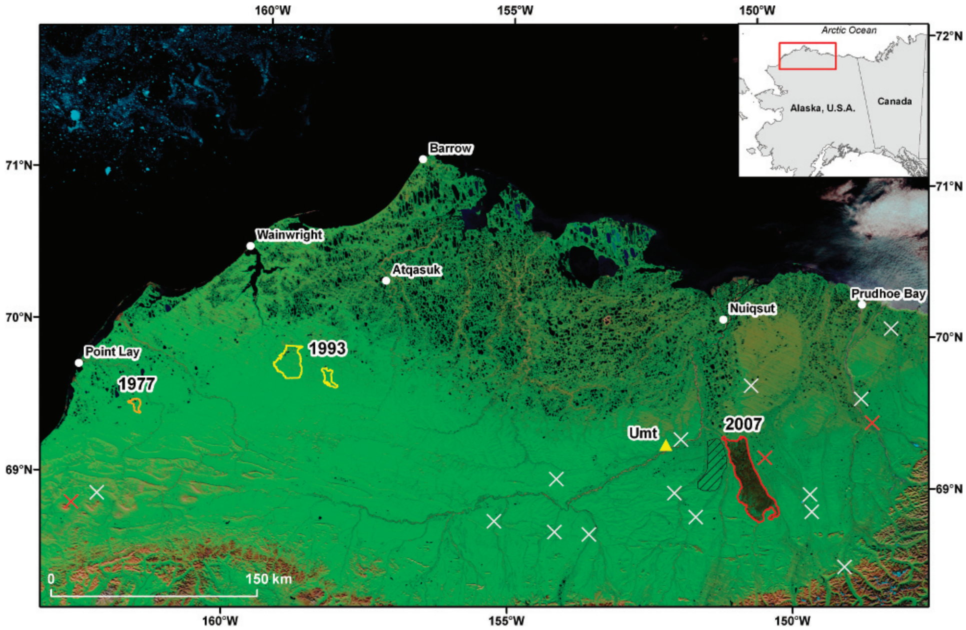

FIGURE 1. MODIS terra image of the Alaskan North Slope showing the three largest tundra fires on record since 1950 (orange = Kokolik River Fire [1977]; yellow = Wainwright Fires [1993]; red = Anaktuvuk River Fire [2007]), gray X's denote smaller tundra fires (<1000 ha) since 1950s, and red X's denote the other three small tundra fires in 2007. Yellow triangle denotes the Umiat climate station, and the hatched polygon the control region for the Normalized Difference Vegetation Index (NDVI) analysis.

Alaska during the 2007 fire year (Fig. 1). The fire occurred primarily in the Arctic Foothills physiographic province of the North Slope (Wahrhaftig, 1965), where the ecosystem is described as upland, shrubby tussock tundra, with gently sloping uplands and ridges in loess and colluvium (>120 m a.s.l.) (Jorgenson and Heiner, 2008). In particular, the vegetation in the burn area was a moist acidic tundra characterized by tussock-forming sedges *Eriophorum vaginatum* and *Carex bigelowi* with >25% cover of dwarf shrubs especially *Ledum palustre*, *Betula nana*, and *Vaccinium vitis-idaea*. Willow (*Salix pulchra*) was the predominant low shrub present, but alders (*Alnus* spp.) also burned along the rivers. In addition to the ARF there were three additional small fires reported on the North Slope of Alaska during 2007, whereas only 18 other fires had previously been reported between 1950 and 2006 (Table 1). Here we present a spatial and temporal reconstruction of the ARF, placed in the context of environmental conditions that characterized 2007, which may explain the extreme behavior and size of the ARF, thus providing information that may prove useful for predicting large tundra fires in subsequent years.

Data and Methods

ARF PROGRESSION

We used Moderate Resolution Imaging Spectroradiometer (MODIS) imagery to reconstruct the progression of the ARF. MODIS imagery from the Terra platform at a spatial resolution of 250 m was obtained through the MODIS Rapid Response System, near real-time subset data, AERONET_Barrow subsets (MODIS

TABLE 1

List of fires that have occurred on the North Slope of Alaska between 1955 and 2007 (AICC, 2008).

Fire season	Name	Latitude (°N)	Longitude (°W)	Area burned (ha)	Start date	Out date	Ignition
1959	162Bettles	69.080	152.000	1	27 Jun 59	n/a	Lightning
1969	Killik River	68.817	153.550	1619	21 Jun 69	8 Aug 69	Lightning
1969	9557 Arpino	70.080	147.830	2	7 Jul 69	n/a	Lightning
1969	9267 Scenic	69.770	150.520	1	3 Jul 69	n/a	Lightning
1976	Dead Horse	68.900	155.250	809	2 Aug 76	1 Sep 76	Trash burning
1977	AIN SSE 38	69.517	161.883	3399	26 Jul 77	12 Aug 77	Lightning
1985	Way up N#2	69.183	154.133	809	9 Aug 85	12 Aug 85	Lightning
1990	031054	69.633	148.500	8	5 Jul 90	22 Jul 90	Lightning
1992	Umiat SE 32	68.917	151.633	4	23 Jun 92	8 Jul 92	Lightning
1993	DCKN178	69.783	158.367	6774	3 Jul 93	17 Aug 93	Lightning
1993	BTTN152	69.433	151.850	65	14 Jul 93	18 Jul 93	Lightning
1993	DCKN190	69.850	159.217	33334	22 Jul 93	18 Aug 93	Lightning
1993	OTZ NW 125	68.417	166.050	10	6 Jul 93	7 Jul 93	Trash burning
1994	FBK N 300	68.833	154.167	8	13 Jun 94	24 Jun 94	Lightning
2001	Kuparuk River	69.027	149.561	344	13 Jun 01	5 Jul 01	Lightning
2003	Surprise Creek	68.902	162.383	223	25 Jun 03	7 Jul 03	Lightning
2004	Kuparuk River	68.912	149.553	2	14 Jun 04	24 Jun 04	Lightning
2004	Sagavanirktok River	68.534	149.039	18	14 Jun 04	17 Jun 04	Lightning
2007	Anaktuvuk River	69.047	150.837	103897	16 Jul 07	10 Oct 07	Lightning
2007	Tupikchak Creek	68.819	162.819	12	14 Jul 07	11 Aug 07	Lightning
2007	Sagavanirktok	69.468	148.336	660	7 Sep 07	9 Oct 07	Lightning
2007	Kuparuk River	69.288	150.336	166	14 Jul 07	10 Aug 07	Lightning

TABLE 2

Descriptive information on the progression of the Anaktuvuk River Fire: centroid of burn perimeter, area burned, change in burn area, rate of change in burn area.

Date	Centroid		Burn area (ha)	Change in area (ha)	Rate of change (ha/day)
	Longitude (°W)	Latitude (°N)			
16 July 2007	150.8425	69.0395	231	N/A	N/A
08 August 2007	150.8279	69.0430	1646	1416	62
27 August 2007	150.7644	69.0498	7262	5615	296
04 September 2007	150.7014	69.0347	15,028	7766	971
11 September 2007	150.6327	69.1206	65,168	50,141	7163
22 September 2007	150.6461	69.1428	92,375	27,207	2473
10 October 2007	150.6385	69.1352	103,897	11,522	606

RSS, 2008). The imagery was available in a Platte Carre projection covering an approximate area bounded by a box with upper left coordinates of 74°30′N and 169°15′W to lower right coordinates of 68°00′N and 144°00′W. Each image set was imported into a remote sensing software package, clipped to an extent that covered the ARF burn perimeter, and reprojected in UTM, zone 6 for manual delineation of the fire perimeter within a Geographic Information System (GIS). We analyzed seven dates of imagery to reconstruct the progression within the limitations of smoke obscured days (Table 2). We also analyzed MODIS 16-day Normalized Difference Vegetation Index (NDVI) composites (MOD13Q1) from 2004 to 2007 for the ARF perimeter and an adjacent 50,000 ha area, to understand the potential role of vegetation condition on the expansion of the fire.

CLIMATOLOGICAL AND METEOROLOGICAL DATA

Modeled, gridded climate data were assessed for the ARF perimeter since the best available long-term weather station at Barrow, Alaska, is over 300 km away and the nearest short-term station is limited to only a few years temporally. Weather variables for the historical period were derived from gridded meteorological data from NCEP's North American Regional Reanalysis (NARR). NARR provides model "observations" for relevant surface variables at high temporal (3-hourly) and spatial (32-km) resolution from 1979 to present (Mesinger et al., 2006). Daily maximum temperature and accumulated precipitation from NARR aggregated over the perimeter of the ARF were bias corrected using PRISM Parameter-elevation Regressions on Independent Slopes Model that incorporates fine-scale geographic controls on precipitation and temperature (Daly et al., 1994). The result is a relatively high-resolution ground-adjusted meteorological data set that provides continuous coverage spatially and temporally from 1979 to present. This data set allows for a comparison of the meteorological conditions experienced in 2007, compared to previous years. Both climatological and the upper and lower deciles of the distribution of daily data were considered. In addition to the high resolution daily gridded data set, long term regional climate anomalies were assessed using NOAA's merged land air and sea surface temperature data set (5 degree horizontal resolution) that extends back to 1880 (Smith et al, 2005).

In addition, the U.S. Geological Survey operates and maintains a network on the North Slope of Alaska that consists of an array of 16 automated meteorological stations continuously monitoring a suite of Global Climate Observing System (GCOS) variables (WMO, 1997), including air temperature, wind speed and direction, snow depth, soil moisture, summer precipitation, incoming and reflected shortwave radiation, surface albedo, and cloudiness. The Umiat station (69°23.741′N, 152°08.568′W, 201 m elevation) data used in this study were collected 65 km west of the ARF in very similar terrain, vegetation type, and elevation. The environmental variables highlighted in this study include snow depth and soil moisture, which are monitored once per hour, and have been aggregated into end of season accumulation and monthly means, respectively. Snow depth is measured with a tripod-mounted (2 m above the ground) ultrasonic distance sensor (Campbell Scientific Model SR50-L) and soil moisture is measured at approximately 15 cm depth with the Stevens Water Monitoring Systems Hydraprobe Soil Moisture Sensor. All environmental data are stored on Campbell Scientific dataloggers and are collected manually twice per year or once per hour via a system of near real-time data telemetry.

BURN SEVERITY MAPPING

Burn severity for the ARF was mapped using the differenced Normalized Burn Ratio (dNBR) method described in Key and Benson (2006), and validated with 19 modified Composite Burn Index (CBI) plots surveyed in the field during the summer of 2008. Paired images were selected that minimized clouds and differences in phenology and solar angles (Key, 2006). A pre-fire Landsat Enhanced Thematic Mapper-plus (ETM+) image was selected for path/row 75/11 from 30 June 1999, and a post-fire Landsat Thematic Mapper (TM) image was selected for path/row 75/11 for 14 June 2008. Both images were atmospherically corrected to reflectance and the dNBR calculated. Burn severity was classified from dNBR using CBI plot thresholds that defined low severity as sites with mixed burned, unburned, and regenerating patches of vegetation, moderate severity as sites mostly burned but with some vegetation remnants and minimal tussock regeneration, and high to extreme severity as sites with complete vegetation and partial soil consumption (Fig. 2). The Pearson product moment correlation coefficient was calculated to determine how well the dNBR represented ground-measured burn severity (i.e. CBI values), and if the level of agreement was significant at the 99 percent confidence level ($p < 0.001$).

Results and Discussion

The total area burned in recorded tundra fires on the North Slope between 1950 and 2007 is roughly 150,000 ha (Fig. 1), of which 100,000 ha were consumed during the ARF in 2007 (Table 1). The ARF was ignited by lightning on 16 July and burned rather slowly until the beginning of August, with a mean burn rate of 62 ha d^{-1} (Fig. 3, Table 2). The ARF continued to burn rather slowly for the remainder of the month and into early September, at which point the fire expanded rapidly in a northerly direction, burning a land area of roughly 7000 ha d^{-1} and

FIGURE 2. Field photos of plots (1 m × 1 m) within the ARF perimeter taken during the summer of 2008, the year following the burn. (a) Typical light-moderate burn severity sample frame and (b) very high burn severity sample frame showing consumption of nearly all vegetation and duff layers.

increasing to a size of 65,000 ha by 11 September. The fire continued to burn rather vigorously through 22 September, burning another 27,000 ha at which point the progression slowed dramatically. Yet the fire continued to burn until around 10 October, when the burn area became covered by snow, reaching a final burn area near 100,000 ha. Thus, from its ignition point along the Nanushuk River, the fire spread east about 20 km to the Itkillik River and burned about 70 km in a north-south direction,

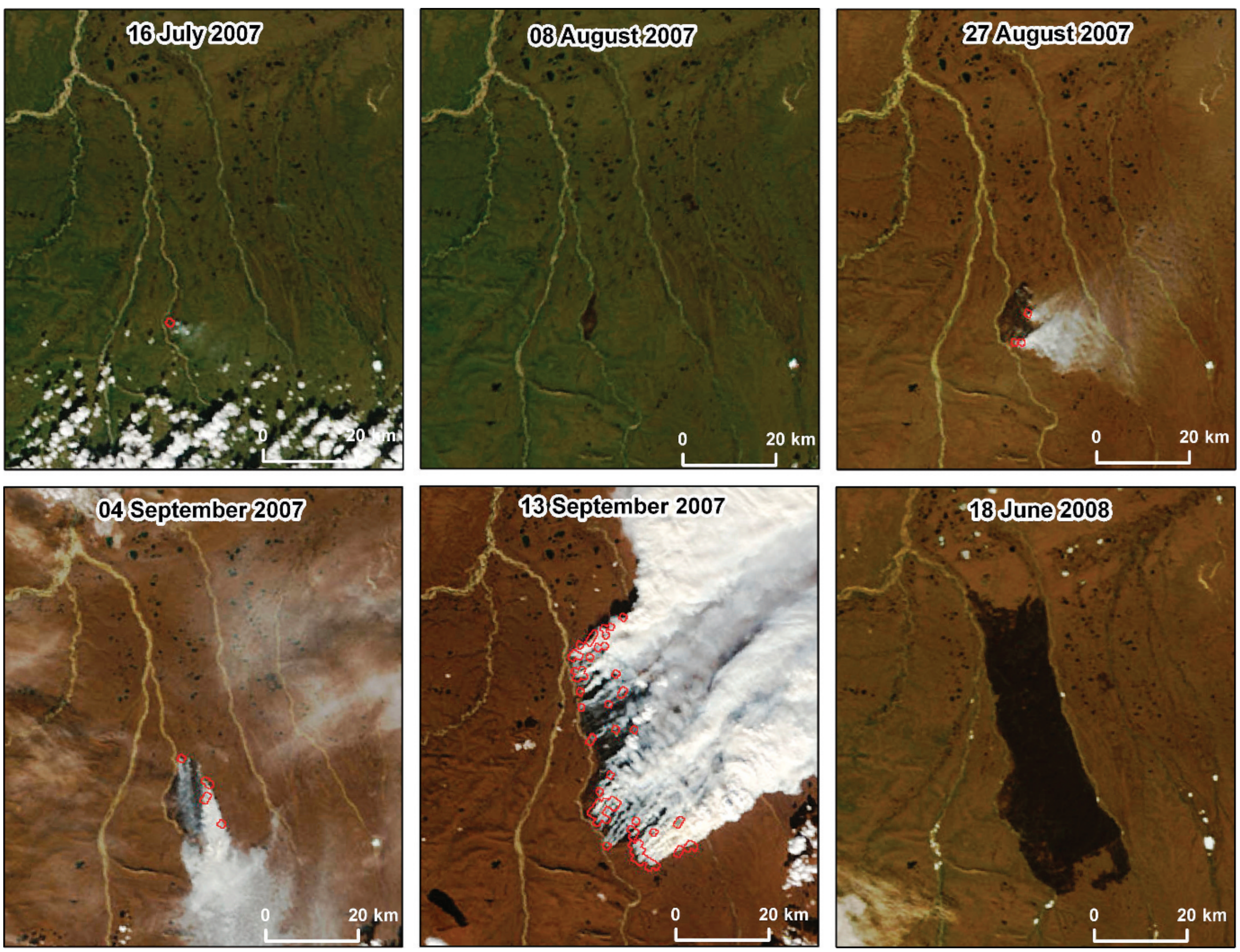

FIGURE 3. MODIS imagery time series showing progression of the ARF during 2007. The red polygons indicate fire pixels within the burn area as determined by an enhanced conceptual fire detection algorithm for MODIS (Giglio et al., 2003).

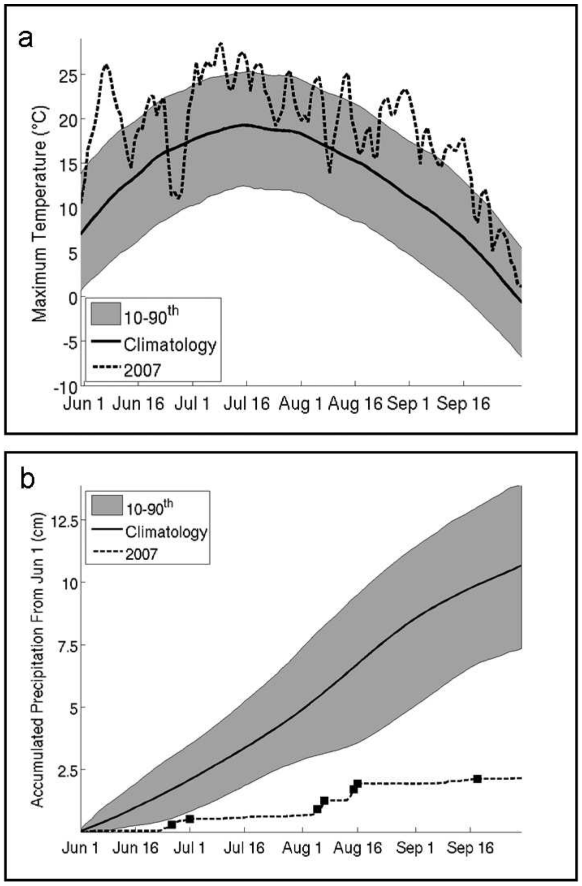

FIGURE 4. (a) Daily maximum temperature and (b) accumulated precipitation over the ARF region in summer 2007 compared to the climatological normal (1979–2007) and the 10th and 90th percentile envelopes.

being confined by drainages as has been noted for other large tundra fires on the North Slope of Alaska (Hall et al., 1978).

2007 ENVIRONMENTAL CONDITIONS DURING ARF

Two sources of information provide insight into the conditions preceding and during the 2007 fire season and the period in which the ARF made the greatest progression. First, gridded climate data provide insights into the temperature and precipitation anomalies that characterized the region both during the entire 2007 fire season and especially during the four week period when fire growth peaked. Monthly surface air temperatures from NOAA's merged land air and sea surface temperature data set (Smith et al., 2005) reveal that July–September temperatures were their warmest over the 129-year record, with a +2.0°C anomaly. This is further reflected in the daily maximum temperature time series (Fig. 4a), which reveals that all but 2 days between July and September were above average and that nearly 90% of the period between mid-August and mid-September (ARF inclusive) fell in the upper decile of the distribution (expected 10%) with daily maximum temperatures 5–10°C warmer than normal.

Climatologically, the ARF region receives the bulk of its precipitation during the months of June through September. The summer of 2007 was the driest of the 29 year record (1979–2007), with the four month total being just over 2 cm, compared to the climatological normal of 10.7 cm (Fig. 4b). Not only was the precipitation deficit concurrent with the ARF the largest in the period of record, but an extended sequence of 33 consecutive days without notable precipitation accumulation (>2 mm) occurred between 16 August and 17 September (Fig. 4b). This sequence of days without precipitation was the second longest noted during July thru September over the period of record, with the longest occurring earlier in the season between 1 July and 4 August. An anomalous positive 500 hPa geopotential height anomaly centered over the Beaufort Sea appears to have led to an enhanced high pressure dome over the North Slope, thereby inhibiting convective thunderstorm activity that may be frequent during the summer months. Likewise, the extratropical stormtrack remained well to the south as a strong zonal jet near 55°N and inhibited disturbances from disrupting the dry-sequence. The alignment of anomalously warm and dry antecedent conditions, capped by a month long period absent of precipitation with anomalously warm and dry conditions appears to have contributed significantly to fostering conditions favorable for the spread of the ARF.

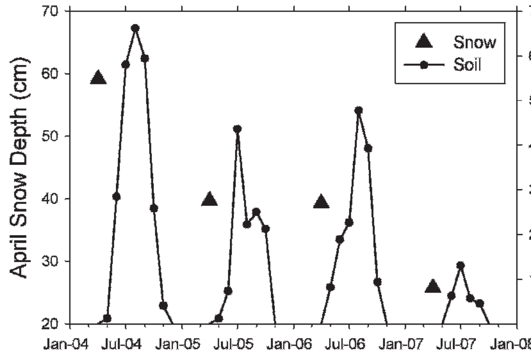

FIGURE 5. Accumulated snow depth measured at the end of April (cm) and volumetric soil moisture content measured at 15 cm below the ground surface at the Umiat meteorological station located 65 km west of the ARF between 2004 and 2007.

Adding to the climatological data, a meteorological station located above the Colville River, near Umiat, has been collecting snow depth and soil moisture data since 2004. Over this four year period, the winter preceding the 2007 fire year was characterized by snow depths about 50% of normal for that period (Fig. 5). Further, the characteristics of the reduced snow pack may have resulted in lowering of early season volumetric soil moisture content (VSMC), with a mean July value of 13%, compared to the 41% mean between 2004 to 2006 (Fig. 5). Owing to the temperature and precipitation conditions described above, VSMC declined to 5% by the middle of August at the site and remained at that level for the remainder of the summer season.

Above-normal temperatures, below-normal precipitation, and extremely low soil moisture conditions typically favor vigorous fire growth in almost any ecotype, but particularly in a tundra ecosystem, where most of the live and dead fuels are conditioned (i.e. the fuel moisture and availability to burn is determined) primarily by the current season meteorology. In the case of the ARF, live fuels (i.e. vegetation) were likely pre-conditioned over the several months leading up to the fire, with the period of greatest fire expansion occurring at the tail end of the most severe seasonal drought in the modeled, gridded climate data set. Analysis of MODIS 16-day NDVI composites confirms a degree of drought-stress with green-up appearing to occur at a slower rate and lower vigor in 2007 when compared to the previous three years, while vegetation senescence appears to have initiated more rapidly in 2007 (Figs. 6a, 6b).

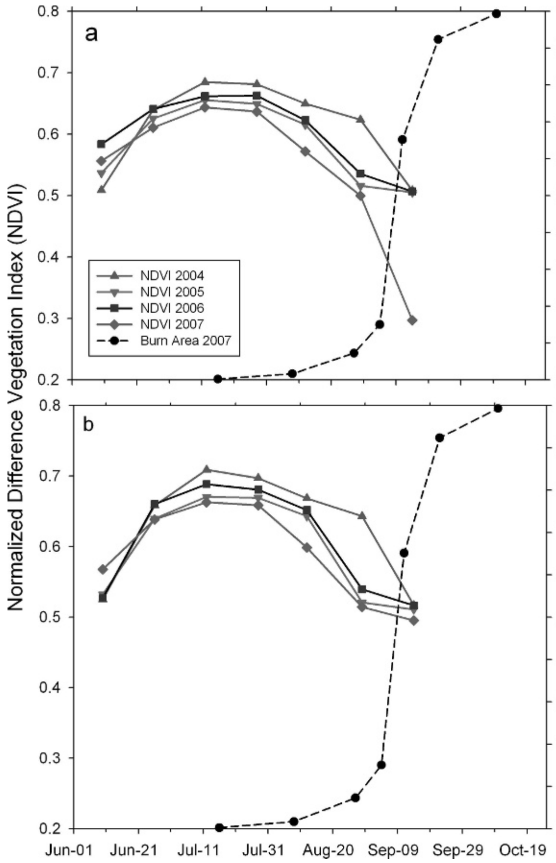

FIGURE 6. MODIS sixteen day NDVI data (aggregated as mean within each respective perimeter) from 2004 to 2007 for the (a) ARF burn area and (b) a control region located to the west to exclude effects from burn scar on NDVI values in 2007. The ARF progression is plotted on the secondary *y*-axis of (a) and (b) to show relation to vegetation condition.

Overlay of the reconstruction of the ARF burn progression with this temporal analysis of NDVI data for the area within the ARF perimeter (Fig. 6a) and a control region to the west (Fig. 6b), shows that the fire started during peak greenness and burned slowly until the vegetation neared complete senescence, at which point a blow-up occurred, indicating that the state of the vegetation may have controlled the burn to some degree. Analysis of wind data at Umiat reveals that coincident with the period of most rapid burning (4–11 September), winds were fairly mild (2–3 m s^{-1}), ranging from southwest (225°) to southeast (162°). Thus, it appears that in addition to the 2007 summer season meteorology, vegetation senescence combined with mild, yet persistent southerly winds, aided in the rapid progression of the fire northward.

BURN SEVERITY

The detailed temporal reconstruction of the ARF coupled with burn severity mapping and field surveys conducted during July 2008 allow us to further analyze the hypothesis that late season conditions lead to more severe burns. CBI transects were installed in 19 locations; 17 associated with the ARF, and 2 associated with the Kuparuk River Fire just to the east of the ARF (Fig. 7). The Kuparuk River Fire ignited on 14 July 2007, and was called out the first week of August. Only 725 ha were burned in the Kuparuk River Fire, which burned primarily at low severity and serves as an excellent contrast to the ARF (Fig. 7). The dNBR values derived from the Landsat imagery had a high Pearson product moment correlation coefficient ($R^2 = 0.814$) to the CBI values, with significance of 99% confidence ($p < 0.001$), and were thus deemed to be an appropriate metric for mapping burn severity over the entirety of the two fires. Classification thresholds were based on CBI classifications determined in the field, and also through assessment of burn severity thresholds for other tundra fires previously mapped on the Seward Peninsula, since no other fires have been mapped for burn severity on the North Slope. Nearly half of the ARF burned at high to extreme severity (47%), while over one-third burned at moderate to high severity (35%). Only 18% burned at low to moderate severity. Comparatively, most of the Kuparuk River Fire burned at low severity (80%), while only 20% burned at moderate severity, and <1% of the Kuparuk Fire burned at high severity (Fig. 7).

These results are consistent with our initial assessment that drought conditions during 2007 promoted vegetation stress and availability to burn, which would be particularly true for the woody scrub species that comprised the majority of the high severity burn area. Burn severity is dependent upon several criteria: fuel availability, fuel abundance, and fire weather, all of which play a critical role in the resulting fire behavior. No previous fires have been mapped by burn severity on the North Slope, but the contrast between the small, low severity Kuparuk Fire and the exponentially larger and more severe ARF further demonstrates the highly anomalous meteorological and climatological conditions that were in place by the end of summer 2007 and subsequently led to vastly different burn severity characteristics between the two fires. However, these findings also highlight the complexities associated with the formation of a large tundra fire on the North Slope, hampering the development of predictive models for future large tundra fires.

Conclusion

The 2007 wildfire season in Alaska was fairly mild compared to 2004 and 2005, however, it was unique in that the largest fire in the state occurred on the North Slope. The ARF consumed more than 100,000 ha and burned for nearly three months, making it the largest and longest burning tundra fire in the region, begging the question: What conditions, both pre-ignition and post-ignition, were present in 2007? We submit that the conditions potentially responsible for this large tundra fire include modeled record high summer temperature and record low summer precipitation, a late-season high-pressure system located over the Beaufort Sea, extremely dry soil conditions throughout the summer, and sustained southerly winds during the period of vegetation senescence.

The size and severity of the ARF provide another example of changing conditions in high latitude regions, along with record reductions in Arctic sea ice extent (Stroeve et al., 2008), increased coastline erosion (Jones et al., 2009), and increased shrub abundance (Sturm et al., 2001; Tape et al., 2006), which may be expected to continue under future climate change scenarios. While the limited wildfire data available for the North Slope make it difficult to model the potential for future large tundra fires, projections of climate change across North America indicate an increase in the frequency and severity of extreme fire danger days (Miller et al., in prep.). For an ecosystem already undergoing rapid change (Sturm et al., 2001; Tape et al., 2006), the ARF may signify a shift in the tundra wildfire regime.

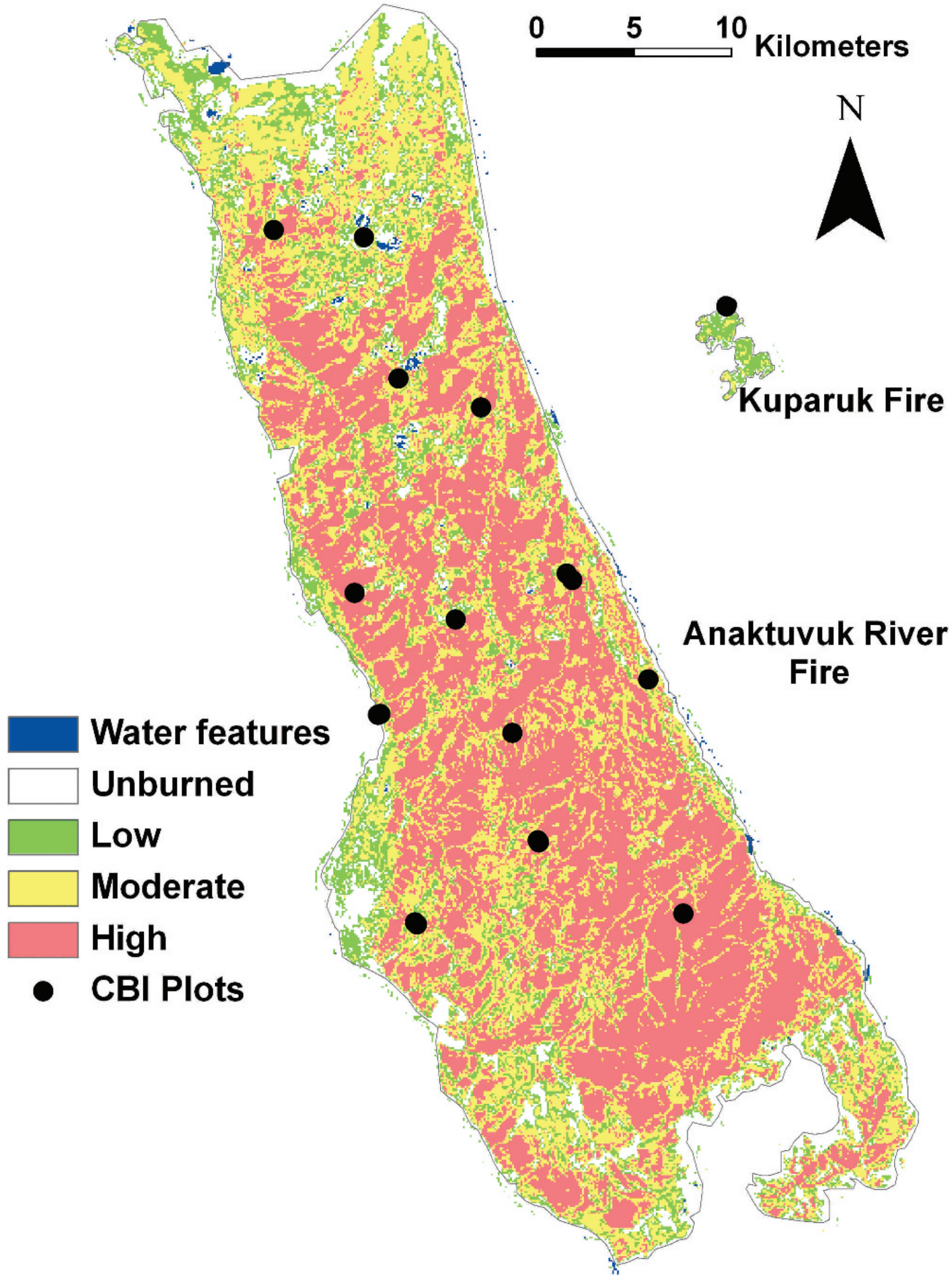

FIGURE 7. Classified burn severity and location of Composite Burn Index (CBI) plots for the ARF and the Kuparuk River Fire.

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