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Active Forest Fire Occurrences in Severe Lightning Years in Alaska

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ABSTRACT

Severe lightning flashes, 120,000 a year or four times more than in the average year, started around 300 fires in each of the three years of 2004, 2005, and 2007 but the burnt area of each year differed considerably. The burnt areas in 2004 and 2005 were the largest and the third largest in the last 55 years (1956-2010), respectively; the burnt area in 2007 was smaller than the average 3,541 km^2. Overall, a comprehensive understanding of active forest fires in severe lightning years in Alaska was achieved based on various fire characteristics including the newly introduced "number of live fires" and "daily fire activity by hotspots" from NASA. These fire characteristics established the fact that severe lightning ignited Alaska's forests in June and July, and that most of the large fires in 2004 and 2005 started and lasted until August. Large numbers of live fires became active during drought and high-air-temperature conditions, which increased the burnt area in 2004. In 2005, continuous precipitation started from June but a large burnt area was also created by a very active forest fire period in August. The burnt area in 2007 was not so large due to continuous precipitation from the beginning of June.

Keyword: active fire, hotspot, lightning, drought, precipitation

1. Introduction

Recent research on boreal forest fires including those in Alaska is now being carried out for a number of reasons such as "emission of global warming gases" and the "fire return interval." In Alaska, recent active forest fires occurred since around 1990 suggesting a short "fire return interval." This fire trend in Alaska appears to contradict recent research results for central Russia and other areas (Wallenius et al., 2011; Flannigan et al., 2005). The authors are now trying to substantiate this by analyzing forest fire activity and lightning occurrence in Alaska.

Although lightning plays a very important role in forest fires as a natural igniter, there have been only few studies associating lightning strikes with fire starts (Fuquay et al., 1972; Wierzchowski et al., 2002; Larjavaara et al., 2005). Wildfires are a major disturbance in interior Alaska, and ecological processes such as post-fire succession, carbon cycling, and permafrost degradation can be dramatically changed directly and indirectly by fires (Johnstone and Chapin, 2006; Kane et al., 2007; Johnstone et al., 2008; O'Donnell et al., 2009). Morris (1934) and Barrows (1954) studied the relationship between thunderstorm days and lightning fires in northwest US and the Rocky Mountains. The authors have studied the weather conditions of anomalous lightning occurrences in 2005 in Alaska and proposed a lightning forecasting method for Alaska using various weather indices (Farukh, Hayasaka, and Kimura, 2011a,b). Price and Rind (1991, 1994) analyzed a global climate model and found that, in association with an increased global air temperature of 4ºC, global mean lightning activity increased by 26%, and would ignite 44% more fires and burn a 78% wider area than under current conditions.

Recent active fire trends in Alaska may be due to so-called global warming as global climate change models predict warmer, longer, and drier summers (Soja et al., 2007) leading to greater fire occurrence and severity (Flannigan et al., 1998; 2000; Gillett et al., 2004; Kasischke and Turetsky, 2006) and a significant change in carbon storage and emissions (Kasischke et al., 2002; Tan et al., 2007). Sandberg et al. (2002) reported that on average, Alaska contributes around 41% of the USA carbon emissions from wildland fires. During the summer, the risk of fire in this region is high due to the relatively small amount of precipitation (Kasischke, 2000). Campbell and Flannigan (2000) reported that the recent trend towards warmer and drier summers is expected to increase the number and size of boreal forest fires. Stevens and Dallison (2005) suggested that recent climate changes in boreal forests could substantially impact the number and size of wildfires in Alaska. Hess et al. (2001) investigated the influence of El Niño weather events on fires and concluded that many of the large fire years occurred just after a warm ENSO episode. The patterns of large fires over the last 50 years in Alaska have been studied by Kasischke et al. (2002) by analyzing the Large Fire Database (LFDB) and other information.

One of the purposes of this paper is to explain the severe forest fires by lightning in 2004 and 2005 that consumed 10% of the forest area of Alaska. A large number of lightning flashes also occurred in 2007 but the burnt area was only one-tenth that of 2004. This may imply that forest fire activity in Alaska is strongly dependent on weather conditions. In this paper, the activities of about 300 forest fires in 2004, 2005, and 2007 occurring as a result of around 120,000 lightning flashes in those years are discussed using various fire characteristics such as fire distribution, fire size, fire duration, fire detection, and number of live fires extracted from fire data by NASA and the AFS (Alaska Fire Service). The effects of weather condition on fire activity are also examined by comparing hotspot data with daily precipitation and air temperature data.

2. Data and Methods

2.1 Lightning Data

Daily lightning data from 1986 to 2010 were obtained from the Alaska Interagency Coordination Center (AICC, 2011), Bureau of Land Management, and Alaska Fire Service (AFS, 2011) with data missing for 1987 and 1989. The data from AFS include the coordinates, dates, times, signal strength, polarity, etc. for each lightning flash, and are detected over larger areas from the Bering Strait to the Canadian mountainous areas (135ºW to 179ºW longitude), and from the tundra in the Arctic region to the forest areas on the southeast coast (70ºN to 50ºN latitude). There are nine lightning detection sensors working in Alaska, and the system was upgraded in 2000. This lightning detection system had a positional accuracy of 2~4 km and a detection efficiency of 40~80% up to 1999 (Dissing and Verbyla, 2003). The detection accuracy and efficiency increased to 0.5~2 km and 80~90%, respectively, from 2000.

2.2 Fire Data (AFS data and MODIS hotspot data)

Fire and area burnt history data from 1956 to 2010 were provided by the University of Alaska Fairbanks (UAF) and Alaska Fire Service (AFS). The data included fire information regarding location, detection date, out date, size (final burnt area), cause, and others. The data were divided into human-caused fires, lightning-caused fires, and other fires.

Moderate Resolution Imaging Spectroradiometer (MODIS) hotspot data were obtained using software developed by NASA based on the NASA ATBD-MOD 14 algorithm (Giglio et al., 2003) where MODIS WGS-84 geographic projection (the "latitude/longitude projection") data were used as input. Each MODIS dataset represents active fire data (NASA, 2002) of the area of interest, i.e., Alaska. The data may include fire detection from MODAPS, the definitive version of Collection 5 (version 5.1), and from MODIS Rapid Response [MRR] (version 5.0). The active fire products of MODIS obtained from the Web

Fire Mapper (Justice et al., 2002) also clearly depict and describe hotspot occurrence in Alaska. The recent daily hotspot data from January 2000 to December 2010 were processed and analyzed to determine fire occurrence tendencies. Various satellite images acquired by *Terra* and *Aqua* (NASA: MODIS Rapid Response System, 2011) from the Aeronet Bonanza subset of North America were comprehensively visualized to compare fire locations with hotspots, and sometimes to obtain information on wind directions. ArcView 3.3 and CAD (VectorWorks, 2010) software were used for accurate plotting of the hotspots on a digital map of Alaska.

2.3 Weather Data

Weather data from Fairbanks Airport were chosen as those typical of Alaskan weather because it may be expected to be the most reliable and has been available for the longest period. Weather data were obtained from the Alaska Climate Research Center, Fairbanks (2011) and the summary of day data of the National Climatic Data Center (2011), and these data were analyzed. The weather components considered were average and maximum air temperatures, sea level pressure, wind speed and direction, and precipitation. In this paper, the weather data from 1990 to 2010 for Fairbanks were mainly used due to unavailability of "daily" data before this period.

3. Lightning Trend and Wildland Fire in Alaska

A time series of the total number of yearly (May to August) lightning flashes from 1986 to 2010 (except 1987 and 1989 due to missing data) from north latitudes 62º to 68.5º and west longitudes 141º to 163º is shown in **Figure 1**. The recent years of 2004, 2005, and 2007 were all extreme in terms of total annual lightning flash numbers within this area. There is about a fourfold difference between these anomalous lightning numbers of around 120,000 each year and average lightning number of around 31,000. Compared to 2005, the largest contrast in the annual lightning flash count was found in 1996 with only around 13,000 annual flashes.

The monthly lightning occurrence is also shown in **Figure 1** with different patterns for May, June, July, and August. As 90% of all lightning flashes occur in June and July, most lightning-caused forest fires in Alaska tend to start in these two months, which is evident from the accumulated curves for the number of fires for 2004, 2005, and 2007 in **Figure 6**. The numbers at the top of the several bars show the rank of the burnt area: 2004 was the largest fire year by burnt area, 2005 was the third largest, and 2007 was the twenty-first largest, though all these three years experienced very similar numbers of lightning flashes.

(I)

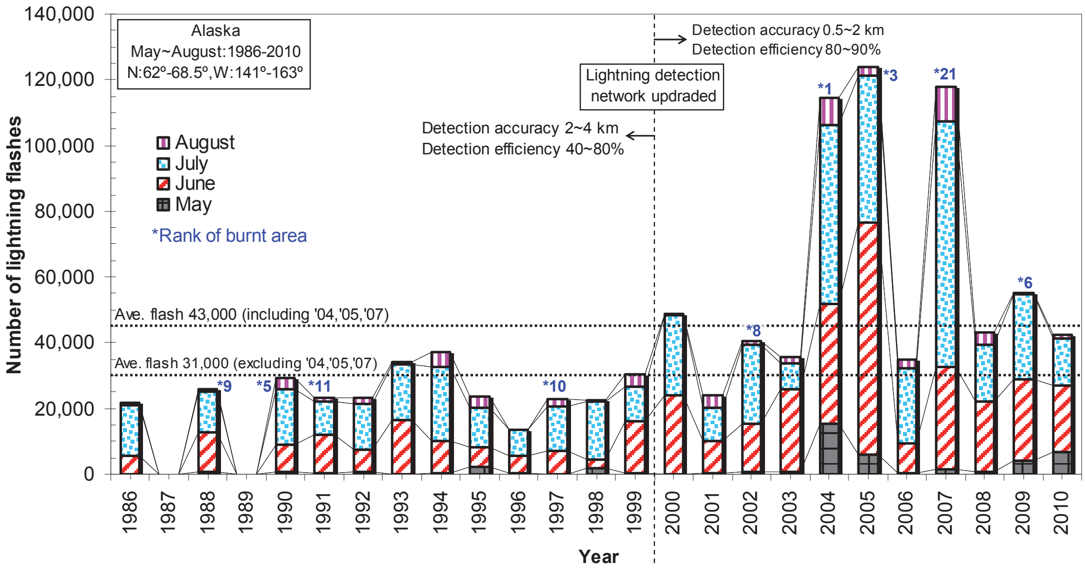

Fig. 1. Yearly and monthly number of lightning flashes in Alaska from 1986 to 2010

This may imply that the burnt area of each year may be mainly influenced by weather conditions after the fire has started. Overall, lightning-caused forest fires are responsible for more than 90% of the annual burnt area in Alaska (Shulski et al., 2005).

Alaska's forest fire distribution by using wildland fire history data from 1956 to 2010 provided by the UAF and AFS is shown in **Figure 2**. In **Figure 2**, the burnt area due to human-caused fire was not very large except in 1969 and 1980. The difference between the human- and lightning-caused burnt area bars clearly indicates that wildland burnt areas are mainly caused by lightning.

In the last 55 years, the average area burnt by lightning-caused fires was calculated to be 3,541 km^2. Recently, large forest fires occurred consecutively in 2004 and 2005. The burnt areas were 26,591 km^2 in 2004 and 18,822 km^2 in 2005, the largest and third largest, respectively, since 1956. Alaska lost 10% of its total boreal forest in these two consecutive years. The burnt area for 2007, the third most severe lightning year discussed here, was only 2,389 km^2. The standard deviations in burnt area (σ_{ba}) for these three years were 4.15 σ_{ba} for 2004, 2.8 σ_{ba} for 2005, and -0.21 σ_{ba} for 2007. Large values of 4.15 for 2004 and 2.8 for 2005 may partly be due to the recent trend in boreal forest fires (Wallenius et al., 2011; Flannigan et al., 2005).

4. Forest Fire Occurrences in Severe Lightning Years (2004, 2005, and 2007)

4.1 Fire Distribution and Fire Size

Lightning-caused forest fire distribution maps of 2004, 2005, and 2007 are shown in **Figure 3**, which also includes tundra fires of 2007. Each fire location in this figure is shown by a black dot. The number of lightning-caused fires was 257, 326, and 259 in 2004, 2005, and 2007, respectively. In addition, circles with different diameters are used to show the size and location of large fires. The diameter of each circle for large fires was determined by considering the final burnt area although it does not show the actual fire size.

In this paper, "very large," "large," and "small" are used to distinguish fires by size of burnt area. "Very large" is used for fires with a burnt area of more than 1,000 km^2, "large" means a burnt area of more than 500 km^2, and "small" is for burnt areas of less than 500 km^2. The fire size distributions for 2004, 2005, and 2007 are shown in **Figure 4**.

Figure 3 shows that most of the fires in 2004, 2005, and 2007 were confined mainly to the center of Alaska, or that fires were distributed uniformly in the

(II)

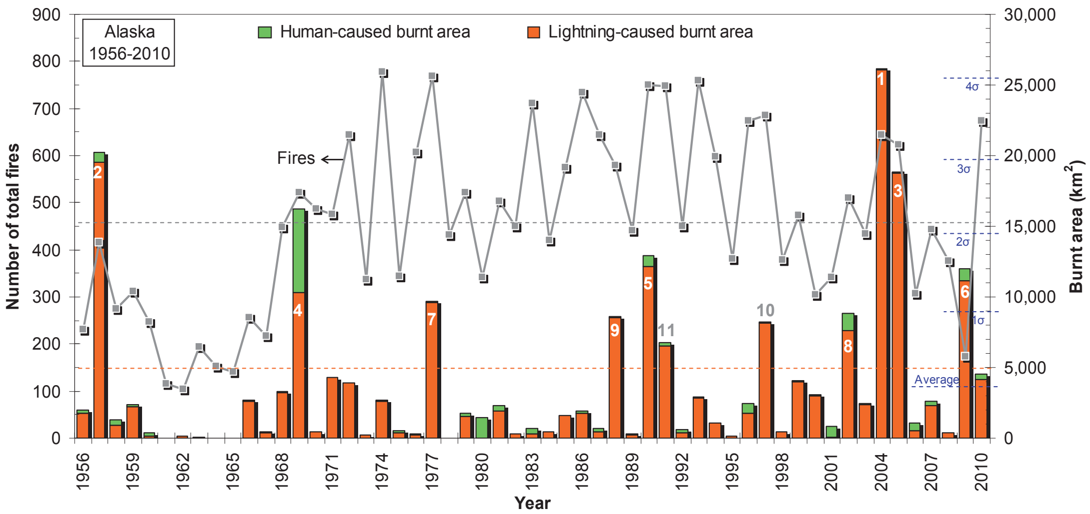

Fig. 2. Burnt area distribution in Alaska from 1956 to 2010

(III)

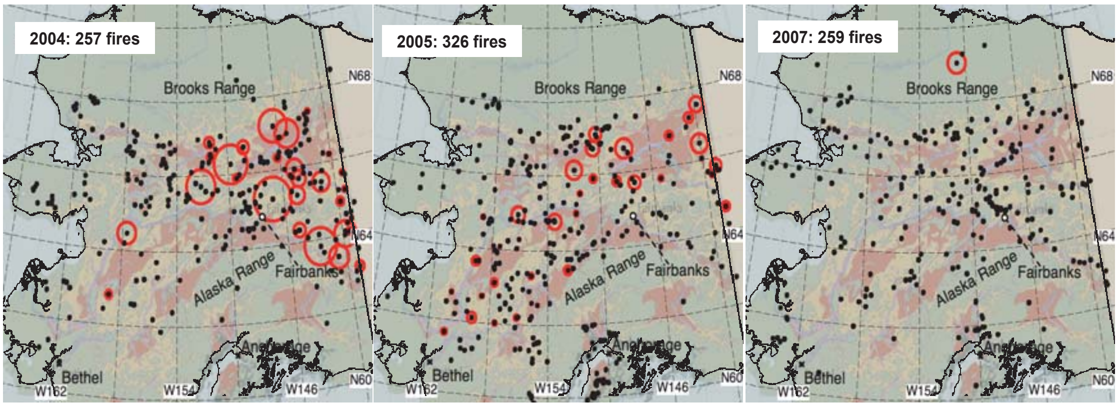

Fig. 3. Fire distribution maps for 2004, 2005, and 2007

(IV)

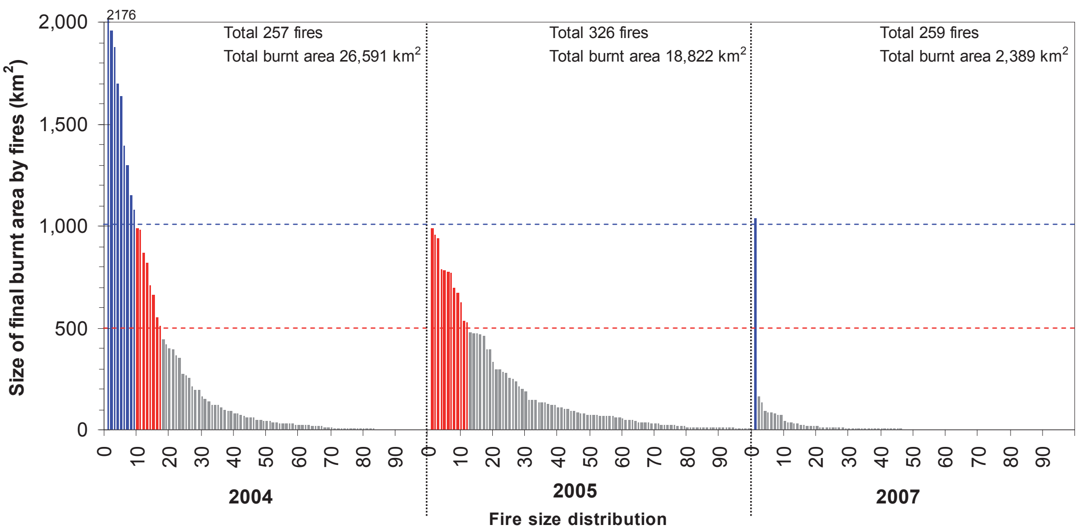

Fig. 4. Fire size distributions in 2004, 2005, and 2007

boreal forest areas of interior Alaska or south of the Brooks Range and north of the Alaska Range. Fires in the northern areas and near the coast were mainly tundra fires. The fire distribution map of 2004 (**Figure 3**) clearly shows several very large fires that occurred concentrically in the eastern part of interior Alaska. None of such large fires occurred in 2005 and 2007, and the fire year 2004 could be termed a "very large fire year." In 2005, fires were distributed uniformly in interior Alaska and the fire sizes were restricted to areas smaller than 1,000 km^2. Thus, fire year 2005 could be termed a "large fire year." The fires in 2007 were also distributed uniformly all over Alaska (**Figure 3**) except on the northern slope of the Brooks Range, near Fairbanks, and near Anchorage. We may call the fire year 2007 a "small fire year."

4.2 Fire Starting Date and Fire Duration

General information on fire sizes, burnt areas, and fire durations is summarized in **Table 1**. The fire durations were calculated by the following equation:

$$\text{Fire duration} = \text{Fire out date} - \text{Fire discovery date} + 1 \qquad (1)$$

where "*fire discovery date*" and "*fire out date*" were derived from the AFS fire data.

Table 1: Fire size and fire duration in 2004, 2005, and 2007

	2004	2005	2007
Number of very large fires (>1,000 km^2)	9	0	1
Number of large fires (500~1,000 km^2)	8	12	0
Number of small fires (<500 km^2)	240	314	258
Total number of lightning-caused fires	257	326	259
Average burnt area (km^2)	103	58	9
Total burnt area (km^2)	26,591	18,822	2,389
Average fire duration (days)	38	32	20
Maximum fire duartion (days)	159	146	157
Average fire starting date (DN)	170	175	168

Table 2 lists the ten largest fires of 2004, 2005, and 2007 with the burnt areas, fire starting dates, and fire durations. There was a total of 257 fires in 2004 (**Table 1**), and 17 large fires (burnt area > 500 km^2) were responsible for 76.5% of the total burnt area in 2004 (26,591 km^2). The total burnt area of nine very large fires (burnt area > 1,000 km^2) corresponded to 53.6% of the total. The reason for the high contribution of fires with large burnt areas may be explained by the starting dates and the long duration of these fires. The average duration of all 2004 fires was 38 days (**Table 1**), while the mean fire duration of the ten largest fires was 133 days, more than four months (**Table 2**). The nine very large fires started mainly in the middle of June and lasted longer, and the largest fire (a boundary fire) in 2004 started on June 12 and lasted 159 days.

Among the 326 fires in 2005, the number of large fires (burnt area > 500 km^2) was 12, which corresponded to 48.1% of the total burnt area (18,822 km^2). The average fire duration of all 2005 fires was 32 days (**Table 1**) with the mean fire duration of the ten largest fires being 92 days or about three months (**Table 2**). These durations are shorter than the fires of 2004 but longer than those of 2007. The 2005 fire starting dates (**Table 2**) show that three large fires started in the middle and the end of July. The duration of these fires was from 63 to 68 days, and these late July fires may have increased the burnt area of 2005 in August.

In 2007, 259 fires occurred and the total burnt area was 2,389 km^2; there was only one large fire, a tundra fire (Anaktuvuk River fire, observed on July 16, with a burnt area of 1,039 km^2). The burnt areas of the remaining 258 fires in 2007 were all smaller than 162 km^2. Small fires in 2007 lasted 20 days on average while the ten largest fires lasted longer, 82 days. This was largely because some of the fires in 2007 started early or from April and May (**Table 2**). This situation implies that some of the fires in less active fire years could last longer and become larger under certain weather conditions.

4.3 Number of Live Fires

In this paper, the term "live fire" is used to explain the overall "active fire" situation in 2004, 2005, and 2007. Live fire was calculated using the "fire discovery date" and the "fire out date" as determined by the AFS data, and the number of daily live fires was summed up; the trend in the number of daily live fires for each year is shown in **Figure 5**.

In 2004, the number of live fires increased from the beginning of June and reached 100 at the end of July.

Table 2: Ten largest fires in 2004, 2005, and 2007

Fire Rank	2004			2005			2007		
	Burnt area (km^2)	Fire starting date (DN)	Fire duration (days)	Burnt area (km^2)	Fire starting date (DN)	Fire duration (days)	Burnt area (km^2)	Fire starting date (DN)	Fire duration (days)
1	2176	12 Jun (164)	159	990	13 Jun (164)	104	1039	16 Jul (197)	85
2	1956	6 Jul (188)	104	958	19 Jul (200)	68	161	5 Jul (186)	87
3	1878	17 Jun (169)	144	938	16 Jun (167)	105	135	28 Apr (118)	157
4	1699	12 Jun (164)	131	785	25 Jul (206)	66	89	6 Jun (157)	100
5	1635	15 Jun (167)	125	783	11 Jun (162)	110	87	23 May (143)	128
6	1395	15 Jun (167)	125	775	24 Jul (205)	63	85	9 Jul (190)	20
7	1296	14 Jun (166)	147	773	16 Jun (167)	77	77	18 Jun (169)	84
8	1152	20 Jun (172)	141	697	30 May (150)	122	73	22 May (142)	29
9	1076	28 Jun (180)	125	674	20 Jun (171)	97	72	8 Jul (189)	94
10	987	14 Jun (166)	126	625	11 Jun (162)	106	40	9 Jul (190)	39
Average	**1525**	**18 Jun (170)**	**133**	**800**	**24 Jun (175)**	**92**	**186**	**17 Jun (168)**	**82**

(V)

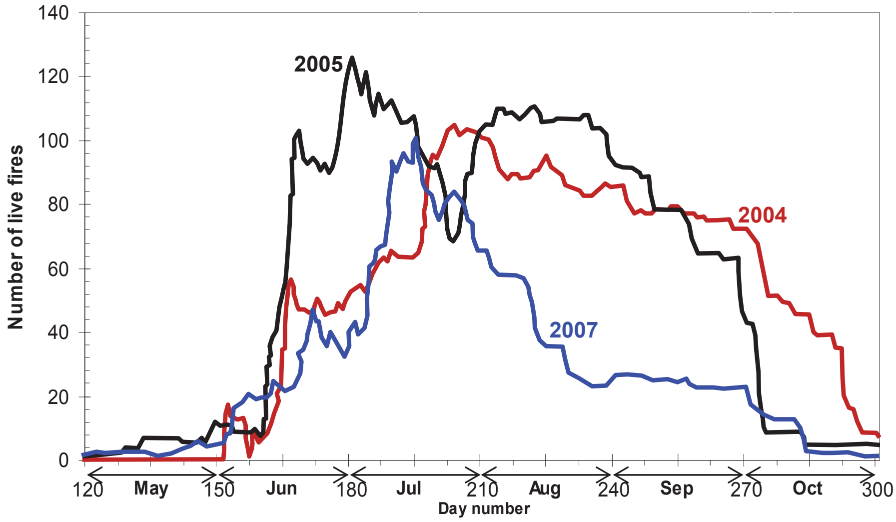

Fig. 5. Number of live fires in 2004, 2005, and 2007

In 2005, the largest number of daily live fires among three years, 125 fires, was observed at the end of June. After the end of June, the number of live fires decreased to 65. But in August, the number of live fires was almost constant, about 100. In 2007, the decreasing trend in the number of live fires started just after the number of fires reached 100, and the number of live fires decreased to 20 at the end of August. Finally, the duration of the periods with large numbers of live fires, i.e., more than 60 consecutive live fires, must be noted: about 90 days in 2004, about 100 days in 2005, and 25 days in 2007. These differences could explain the differences in the total final burnt area of each year.

4.4 Lightning and Fire Occurrences

Figure 6 shows the daily occurrences of lightning (from the upper *x*-axis) and fires (from the lower *x*-axis) from May to August in 2004, 2005, and 2007. The two line curves from the upper and lower *x*-axes represent the accumulated number of lightning flashes and fires detected by AFS, respectively.

Figure 6 shows that the number of fires in 2004, 2005, and 2007 closely coincided with the lightning occurrence tendencies. But several different characteristics of the lightning and fire occurrences are also notable in this figure, such as at the third peak of lightning at the beginning of July in 2004, and at the third and fourth peak of lightning in the middle of July in 2005. These discrepancies arise due to the different detection systems for lightning and fires, as well as to the so-called time lags mainly due to the schedules of survey flights by AFS and holdover fires (Hayasaka and Lynch, 2001).

The situation around lightning and fire occurrences may be understood by considering the gradient of the line curves for the accumulated number of lightning flashes and fires in **Figure 6**. Steep and large gradients of the curves show a "peak" and a "most intense period" for lightning and fire occurrences, with low and zero gradients of the curves suggesting no or few occurrences of lightning and fires.

The accumulated curve for lightning shows four major lightning peaks in 2004. Two major peaks and one continuous period of lightning in July are shown by the curve for 2005. One continuous active lightning period occurred in July of 2007. Under the different lightning occurrence patterns in these three years, the accumulated AFS fire curves showed different fire occurrence patterns. There is one sharp fire peak in the middle of June in both 2004 and 2005, but only one small peak in 2007. Fire occurrence in the middle of June is one of the major fire characteristics in Alaska. In 2004, the one fire peak in June corresponds to the second lightning peak, and the number of fires continuously increased until the third fire peak in the middle of July. In 2005, the one sharp fire peak corresponded

(VI)

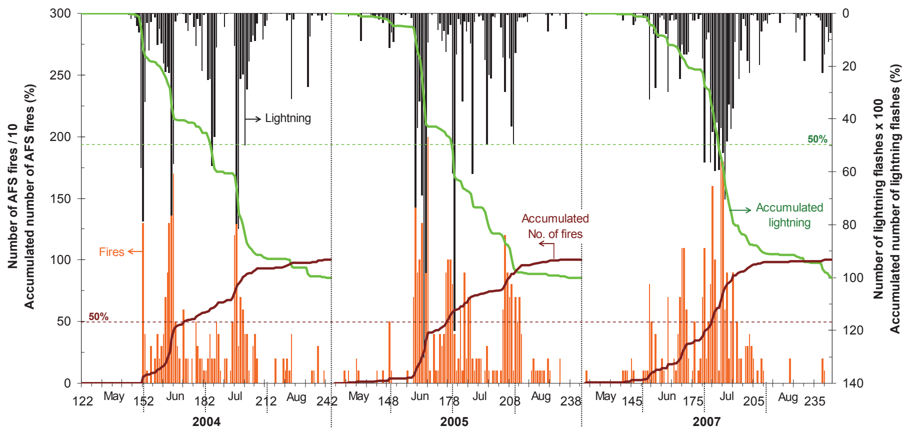

Fig. 6. Number of lightning flashes and fires (AFS) in 2004, 2005, and 2007

to the first sharp peak of lightning, and fires occurred continuously until the beginning of August. In 2007, the occurrence of fires started from the beginning of June and lasted until the middle of July following a very similar fire occurrence rate as in the other two years.

4.5 Onset of Large Fires and Final Burnt Area

To show the behavior of each individual fire, an evaluation of the burnt areas was carried out by summing up the final burnt area of each fire for the same fire detection date. The accumulated burnt area for the same fire detection date was calculated by the following equation:

$$(Accumulated\ burnt\ area)_{DN} = \sum_{i=1}^{n} FBA_{DN,\ i} \quad \text{.........................., (2)}$$

where *DN* is the "specified day number," *FBA* is the "final burnt area," and *n* is the number of fires detected on the same *DN*.

The bars from the lower *x-axis* in **Figure 7** represent daily burnt areas and show when the larger fires occurred. But with only this bar graph, it was not possible to identify the severity of the fires i.e., fire expansion, final burnt area, and overall fire activities. To compensate for this, an accumulated curve (line curve from the lower *x-axis*) for the percentage of the total burnt area was added to **Figure 7**. The steep gradient of this curve could show the tendency of severe fire occurrence in each year.

In 2004, one very severe fire occurred in the middle of June and the percentage of accumulated burnt area

(VII)

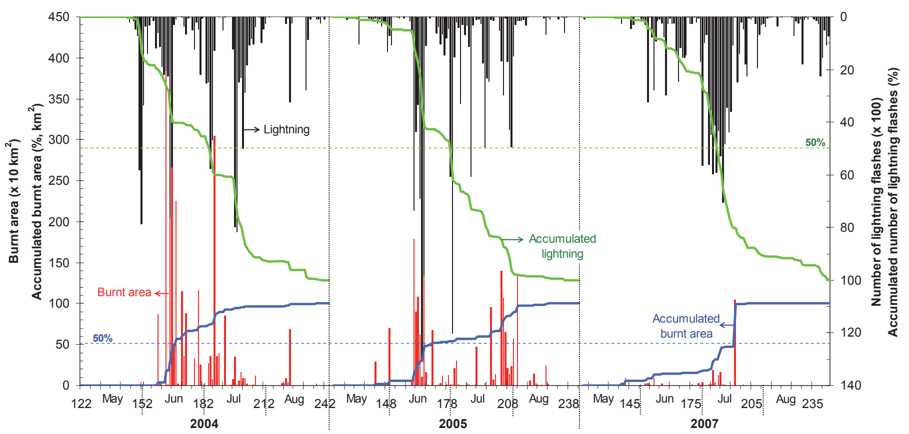

Fig. 7. Number of lightning flashes and fire occurrences (burnt areas) in 2004, 2005, and 2007

reached 50%. A severe fire was also found in the middle of June 2005. But after reaching 50%, two different fire patterns for both of the years were found. In 2004, the percentage of accumulated burnt area reached 90% at the beginning of July but this percentage (90%) was reached at the beginning of August in 2005. This implies that severe fires occurred concentrically from the middle of June to the beginning of July in 2004. But there were two severe fire periods in 2005: in the middle of June and at the end of July. In 2007, some small fires occurred at the beginning of July and the percentage of accumulated burnt area reached 90% just after a severe fire in the middle of July.

Finally, it is necessary to bear in mind that the above severe fire occurrence trends only interpret large fire occurrences, and are not directly related to fire activities or fire propagation after ignition by lightning. This suggests that assistance from other data such as daily hotspot data and weather data is needed so as to evaluate the fire activities of each year.

4.6 Fire Activity and Weather

Daily hotspot data from NASA-MODIS are used here to evaluate fire activity and its interaction with weather conditions like precipitation and air temperature. For this purpose, weather data of the Fairbanks station could not explain all Alaskan weather changes but could be used as a weather indicator representative of weather conditions in the interior of Alaska.

4.6.1 Fire Activation by Drought and Precipitation

The accumulated precipitation for 2004, 2005, and 2007 (dotted curve), and the average accumulated precipitation for 1990 to 2010 (solid curve), with bars for the number of daily hotspots from May to August are shown in **Figure 8**. The standard deviations (+1 σ_{ap} and -1 σ_{ap}) for the average accumulated precipitation with the σ_p values for 2004, 2005, and 2007 are shown on the *y*-axis for each year. The gradient (dashed line) of the accumulated precipitation curves in **Figure 8** expresses the overall precipitation pattern. Where the gradient is flat or zero, it shows the occurrence of a rainless day or drought. The average accumulated precipitation curve in **Figure 8** shows a constant gradient from the beginning of June to the end of August, and the average precipitation rate during the fire season (May to August) is about 1.5 mm/day in Alaska. The total accumulated precipitation in 2004, 2005, and 2007 was 114 mm (-0.86 σ_p), 223 mm (1.13 σ_p), and 195 mm (0.63 σ_p), respectively.

There were three distinct periods and peaks of daily hotspots in 2004 (bars in **Figure 8**), and they occurred during the two drought periods. This result suggests that the fires in 2004 became active in the two drought periods, the one drought period being in June and July and the other being in August. The fires occurring from the beginning of June were not so active due to precipitation from the middle of May 2004.

The largest peak in the number of daily hotspots in 2004, 2005, and 2007 occurred in the middle of Au-

(VIII)

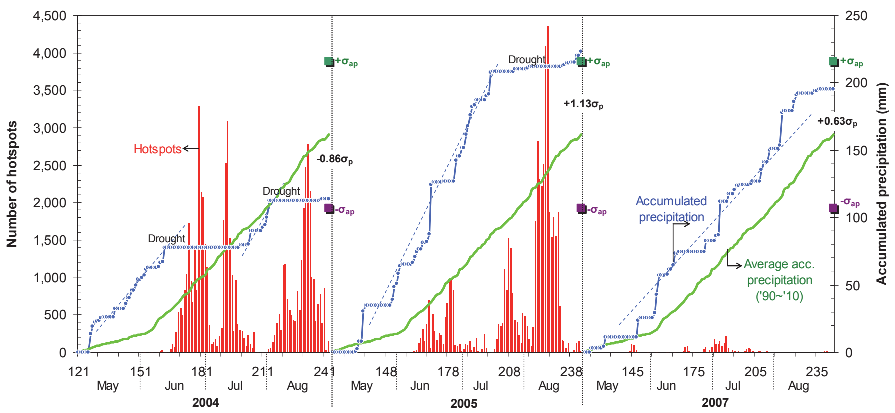

Fig. 8. Accumulated precipitation and daily hotspots (fires) in 2004, 2005, and 2007

gust 2005 (**Figure 8**). This active fire period occurred due to drought from the middle of July. Other fires in June and July 2005 may have been suppressed by the continuous precipitation that started from the middle of May. The precipitation rate from the middle of May to the middle of July 2005 was 3.5 mm/day, and this was around twice the average.

There was no noticeable hotspot peak in 2007. This may be explained by different lightning occurrence tendencies in 2004, 2005, and 2007 found in **Figures 6** & **7**. Active lightning occurrences in the middle of June in 2004 and 2005 left fatal fires in number and burnt area as shown in **Figures 6** & **7**. On the other hand, a small but notable lightning occurrence could be found in the middle of June in 2007. Active lightning occurrence in 2004 and 2005 could be partially explained by the high maximum air temperature in **Figure 9**. Other weather factors related to active lightning occurrence in Alaska have already been clarified by the authors (Farukh, Hayasaka, Kimura, 2011a,b).

4.6.2 Fire Activity and Air Temperature

To evaluate the effect of the "maximum air temperature" (T_{max}) on fire activity, the daily T_{max} change along with hotspots is shown in **Figure 9** for each of the years 2004, 2005, and 2007. In this figure, the average T_{max} is shown by the thick solid line curve and the other two line curves (shown by dotted lines) are for the standard deviations (+1 σ_t and -1 σ_t). The monthly averages of T_{max} for each year are also shown, by heavy dotted horizontal lines.

Figure 9 shows that most of the hotspot periods in 2004 and 2005 coincided with higher-T_{max} periods and days. The T_{max} of most of these days exceeded 30ºC. In addition, a few hotspot peaks like at the end of June and the middle of August 2004 and the middle of August 2005 occurred at the final stage of the higher-T_{max} periods, when the temperatures exceeded +1 σ_t. These trends support the idea that forest fires become active during high-temperature periods with rainless or drought conditions.

Table 3: Factors for the normalized standard deviation (σt) of each monthin 2004, 2005, and 2007

	May	June	July	August
2004	0.18	2.20	0.54	1.94
2005	1.13	0.00	-0.36	0.29
2007	0.11	0.24	0.51	1.31
***Ave. T_{max} (ºC)**	16.4	22.1	22.7	18.9
1 σ_t	2.50	1.39	1.77	1.95

*Average in the period from 1990 to 2010

The effect of T_{max} on the fire behavior of each year is shown in **Table 3**. Due to the large fluctuations in daily temperature, normalized standard deviations of monthly average temperatures are used here. **Table 3** shows that the temperatures in June and August 2004 were significantly higher (+2.20 σ_t and +1.94 σ_t, respectively) than the average. These high temperatures could be one of the causes of the largest fire occurrences in 2004. Although the monthly temperature of August 2005 was not very much higher (+0.29 σ_t), the temperatures at the beginning of August were significantly higher (**Figure 9**). These results suggest that air

(IX)

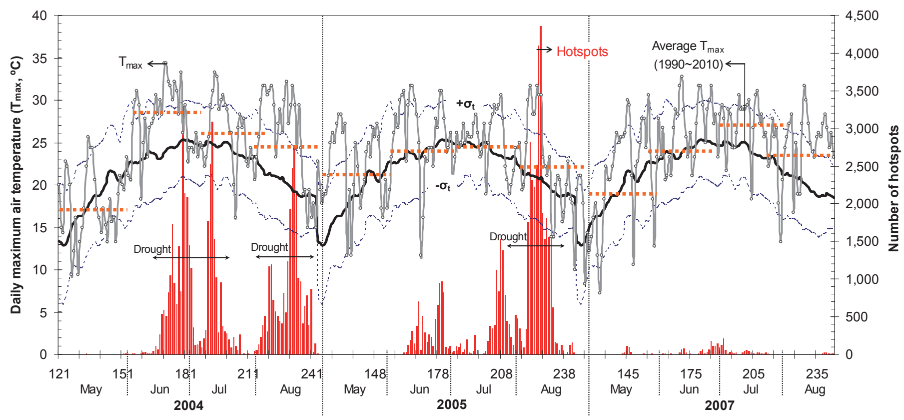

Fig. 9. Daily maximum air temperature (T_{max}) and hotspots (fires) in 2004, 2005, and 2007

temperature is also a key factor in active forest fires in Alaska.

4.7 Summary of Fire Characteristics

A number of fire characteristics together with fire and lightning occurrences are listed in **Table 4**. In this table, several kinds of downward arrow marks for lightning and precipitation, and upward arrow marks for fire numbers and areas, hotspots, and drought, are used. The arrow sizes express the severity, and the percentages show the accumulated value of listed fire characteristics at that time point.

In **Table 4**, 50% of lightning tended to occur before the beginning of July for all the years (shown by "↓50%"), and about 70% of the fires in 2004 and 2005 had already started before the beginning of July (**Figure 6**). This situation would occur due to differences in precipitation pattern and moisture condition of the forest floor. Thus, fires starting before the beginning of July could possibly remain active if they are surrounded by enough fuel, and the duration of some of these fires is more than 100 days (**Table 2**).

The arrows for the "accumulated final burnt area" (AFBA) in **Table 4** show the approximate date of fire starting as well as the date of severe fires for 2004, 2005, and 2007. The AFBA clearly shows that severe fires started mainly in June and July in the case of 2004 (**Table 4** & **Figure 7**). The hotspot numbers suggest severe fires in 2005 starting in June and July as well as in August. Fires in 2004 became active in three major fire periods: at the end of June, the middle of July, and August (**Table 4** & **Figure 8**). The most severe fire activity occurred in the middle of August 2005, and there was only small fire activity in 2007. The occurrence of two long drought periods (**Table 4**) of more than 30 days in 2004 may have assisted fire expansion. The considerably high temperature (T_{max} = +2.20 σ_t, **Figure 9** & **Table 3**) in June 2004 may have been a factor in the active fires. The total precipitation from May to August 2005 was larger than average (+1.13 σ_p) but more than 100 live fires became very active during the long drought from the middle of July. In August 2007, the temperatures were high (+1.31 σ_t) but fires were not active due to the continuous precipitation from the beginning of June.

Table 4: Fire and lightning occurrences, and fire characteristics in 2004, 2005, and 2007

Year	Month / DN	150	160	170	180	190	200	210	220	230	240	Remarks
		←	June	→	←	July	→	←	August	→		
2004	Lightning	↓	↓	↓	↓50%	↓	↓90%	↓	↓	↓		4 major peaks
	Fire (num.)	↑	↑50%	↑	↑70%	↑	↑90%					1 major peak
	Fire (area) AFBA		↑50%	↑	↑70%	↑90%						1 major peak 1 small peak
	Hotspot		↑	↑	↑	↑	↑	↑	↑	↑		3 major peaks 3 major periods
	Number of live fires	10	30	50	50	65	**100**	**90**	**90**	**85**	**80**	
	Precipitation	↓						↓				114 mm (-0.86σ_p)
	Drought		↑	↑	↑	↑		↑	↑	↑	↑	2 periods
	T_{max} (SD)		+2.20σ_t			+0.54σ_t			+1.94σ_t			
2005	Lightning		↓	↓	↓50%	↓	↓90%	↓	↓	↓		2 major peaks
	Fire (num.)		↑	↑50%	↑70%	↑	↑90%	↑				1 major peak
	Fire (area) AFBA		↑50%	↑	↑	↑	↑70%	↑90%				1 major peak 1 small peak
	Hotspot		↑	↑	↑	↑	↑	↑	↑	↑		2 major peaks 2 major periods
	Number of live fires	10	50	**90**	**110**	**105**	80	**105**	**105**	**105**	**90**	
	Precipitation	↓	↓	↓	↓							223 mm (+1.13σ_p)
	Drought			↑		↑	↑	↑	↑	↑	↑	1 period
	T_{max} (SD)		0.00σ_t			-0.36σ_t			+0.29σ_t			
2007	Lightning	↓	↓	↓	↓50%	↓	↓	↓90%	↓	↓		1 continuous peak
	Fire (num.)	↑	↑	↑	↑50%	↑70%	↑90%					1 peak
	Fire (area) AFBA				↑		↑ 50-90%					2 small peaks
	Hotspot				↑							
	Number of live fires	10	20	35	60	**85**	**80**	60	30	25	25	
	Precipitation	↓	↓	↓	↓	↓	↓	↓				195 mm (+0.63σ_p)
	Drought		↑	↑		↑			↑	↑	↑	
	T_{max} (SD)		+0.24σ_t			+0.51σ_t			+1.31σ_t			

Explanation of arrow markings:
↓ ↓ ↓ used for lightning and precipitation, ↑ ↑ ↑ used for fire number, fire area (AFBA), hotspots, and drought, and arrangement of arrows from left to right indicates the severity from high to low.

5. Conclusions

Severe lightning flashes, 120,000 a year or more than four times the annual average, started around 300 fires in each year of 2004, 2005, and 2007. Several fire characteristics introduced by the authors such as fire duration, accumulated final burnt area (AFBA), and number of live fires were found to be effective in explaining forest fire activity in Alaska. Discussion focusing on the various fire characteristics may reach the following conclusions or causes of forest fires in each of the years surveyed.

1. The 2004 forest fires left the historically largest annual burnt area in Alaska mainly due to severe fire occurrence under drought (-0.86 σ_p) and high-air-temperature (+2.20 σ_t) conditions in June. Three active fire periods in June, July, and August also triggered the largest burnt area under drought conditions, with a large number of live fires (> 80) in August.
2. The forest fires of 2005 were characterized by severe fire occurrence in June, July, and August. The most active fire period in August started in July under drought with a large numbers of live fires (> 100) despite the relatively heavy precipitation from May to the beginning of July (+1.13 σ_p). These conditions resulted in the third-largest annual burnt area.
3. The 2007 forest fires left the twenty-first-largest annual burnt area with no severe fire occurrence under non-active lightning conditions in June, and limited fire occurrence under severe lightning and precipitation (+0.63 σ_p) in July. Although there was one very large tundra fire, there were no August fires even with drought and high-air-temperature conditions (+1.31 σ_t).

Finally, it could be concluded that severe fires in Alaska tend to occur from the middle of June to the beginning of July, and that these severe fires could become active even in August under drought and high-air-temperature conditions.

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References

Alaska Climate Research Center, 2011. http://climate.gi.alaska.edu/Climate/Location/Interior/Fairbanks.html

Alaska Fire Service (AFS), 2011. http://fire.ak.blm.gov/afs/

Alaska Interagency Coordination Center (AICC), 2011. http://afsmaps.blm.gov/imf_lightning/imf.jsp?site=lightning

Barrows, J. S., 1954. "Lightning Fire Research in the Rocky Mountains," *Journal of Forestry* 52, pp. 845-847.

Campbell, I. D. and M. D. Flannigan, 2000. "Long-Term Perspectives on Fire-Climate-Vegetation Relationships in the North American Boreal Forest," *Ecological Studies* 138, pp. 151-172, Springer.

Dissing, D. and D. L. Verbyla, 2003. "Spatial Patterns of Lightning Strikes in Interior Alaska and Their Relations to Elevation and Vegetation," *Can. J. For. Res.* 33, pp. 770-782.

Farukh, M. A., Hayasaka, H., and K. Kimura, 2011a. "Characterization of Lightning Occurrence in Alaska Using Various Weather Indices for Lightning Forecast," *Journal of Disaster Research* 6(3), pp. 343-355.

Farukh, M. A., Hayasaka, H., and K. Kimura, 2011b. "Recent Severe Lightning Occurrences in Alaska –The Case of June 2005 –," *Journal of Disaster Research* 6(3), pp. 321-330.

Flannigan, M. D., Bergeron, Y., Engelmark, O., and B. M. Wotton, 1998. "Future Wildfire in Circumboreal Forests in Relation to Global Warming," *Journal of Vegetation Science* 9, pp. 469-476.

Flannigan, M. D., Logan, K. A., Amiro, B. D., Skinner, W. R., and B. J. Stocks, 2005. "Future Area Burned in Canada," *Climatic Change* 72, pp. 1-16.

Flannigan, M. D., Stocks, B. J., and M. B. Wotton, 2000. "Climate Change and Forest Fires," *Science of the Total Environment* 262, pp. 221-229.

Fuquay, D. M., Taylor, A. R., Hawe, R. G., and C.W. Schmid, Jr. 1972. "Lightning Discharges That Caused Forest Fires," *Journal of Geophysical Research* 77, pp. 2156-2158.

Giglio, L., Descloitres, J., Justice, C. O., and Y. Kaufman, 2003. "An Enhanced Contextual Fire Detection Algorithm for MODIS," *Remote Sensing of Environment* 87, pp. 273-282.

Gillett, N. P., Weaver, A. J., Zwiers, F. W., and M. D. Flannigan, 2004. "Detecting the Effect of Climate Change on Canadian Forest Fires," *Geophysical Research Letters* 31, L18211.

Hayasaka, H. and M. Lynch, 2001. "Forest Fires and Lightning in Alaska," Proc. of 9th Symp. on Joint Siberian Permafrost Studies between Japan and Russia in 2000, 181-187.

Hess, J. C., Scott, C. A., Hufford, G. L., and M. D. Fleming, 2001. "El Niño and Its Impact on Fire Weather Conditions in Alaska," *Int. J. of Wildland Fire* 10, pp. 1-13.

Johnstone, J. and F. S. Chapin, 2006. "Effects of Soil Burn Severity on Patterns of Post-Fire Tree Recruitment in Boreal Forests," *Ecosystems* 9, 14-31.

Johnstone, J. F., Hollingsworth, T. N., and F. S. Chapin, 2008. "A Key for Predicting Successional Trajectories in Black Spruce Stands of Interior Alaska," USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-767 (Portland, OR).

Justice, C. O., Giglio, L., Korontzi, S., Owens, J., Morisette, J. T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F., and Y. Kaufman, 2002. "The MODIS Fire Products," *Remote Sensing of Environment* 83, pp. 244-262.

Kane, E. S., Kasischke, E. S., Valentine, D. W., Turetsky, M. R., and A. D. McGuire, 2007. "Topographic Influences on Wildfire Consumption of Soil Organic Carbon in Interior Alaska: Implications for Black Carbon Accumulation," *Journal of Geophysical Research* 112, G03017.

Kasischke, E. S. and M. R. Turetsky, 2006. "Recent Changes in Fire Regime across the North American Boreal Region – Spatial and Temporal Patterns of Burning across Canada and Alaska," *Geophysical Research Letters* 33, L09703.

Kasischke, E. S., 2000. "Boreal Ecosystems in the Global Carbon Cycle," *Ecological Studies* 138, pp. 19-30, Springer.

Kasischke, E. S., Williams, D., and D. Barry, 2002. "Analysis of the Patterns of Large Fires in the Boreal Forest Region of Alaska," *Int. J. of Wildland Fire* 11, pp. 131-144.

Larjavaara, T., Pennanen, K. J., and T. J. Tuomi, 2005. "Lightning That Ignites Fires in Finland," *Agriculture and Forest Meteorology* 132, pp. 171-180.

MODIS Rapid Response System, 2011. http://rapidfire.sci.gsfc.nasa.gov/subsets/?subset=AERONET_Bonanza_Creek

Morris, W. G., 1934. "Lightning Storms on the National Forests of Oregon and Washington," Forest Service, Pacific Northwest Forest Experiment Station, Portland, Oregon, USA.

NASA/University of Maryland, 2002. "MODIS Hotspot / Active Fire Detections, Data set," MODIS Rapid Response Project, NASA/GSFC [producer], University of Maryland, Fire Information for Resource Management System [distributors], available on-line [http://maps.geog.umd.edu].

National Climatic Data Center, 2011. http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?akAFAI

O'Donnell, J. A., Turetsky, M. R., Harden, J. W., Manies, K. L., Pruett, L. E., Shetler, G., and J. C. Neff, 2009. "Interactive Effects of Fire, Soil Climate, and Moss on CO_2 Fluxes in Black Spruce Ecosystems of Interior Alaska," *Ecosystems* 12, 57-72.

Price, C. and D. Rind, 1991. "Lightning Activity in a Greenhouse World," Proc. of 11th Conference on Fire and Forest Meteorology 11, pp. 598-604.

Price, C. and D. Rind, 1994. "The Impact of a 2 x CO_2 Climate on Lightning Caused Fires," *Journal of Climate* 7, pp. 1484-1494.

Sandberg, D. V., Ottmar, R. D., Peterson, J. L., and J. Core, 2002. "Wildland Fire on Ecosystems: Effects of Fire on Air," USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-42, Vol. 5 (Ogden, UT).

Shulski, M., Wendler, G., Alden, S., and N. Larkin, 2005. "Alaska's Exceptional 2004 Fire Season," 6th Symposium on Fire & Forest Meteorology, Canmore.

Soja, A. J., Tchebakova, N. M., French, N. H. F., Flannigan, M. D., Shugart, H. H., Stocks, B. J., Sukhinin, A. I., Parfenova, E. I., Chapin, F. S., and P. W. Stackouse, 2007. "Climate-Induced Boreal Forest Change: Predictions versus Current Observations," *Global and Planetary Climate Change* 56, pp. 274-296.

Stevens, E. and D. Dallison, 2005. "An Extraordinary Summer in the Interior of Alaska," P3.24, report on the panel at the University of Alaska Fairbanks.

Tan, Z., Tieszen, L. L., Zhu, Z., Liu, S., and S. M. Howard, 2007. "An Estimate of Carbon Emissions from 2004 Wildfires across Alaskan Yukon River Basin," *Carbon Balance and Management* 2, p. 12.

Wallenius, T., Larjavaara, M., Heikkinen, J., and O. Shibistova, 2011. "Declining Fires in Larix-Dominated Forests in Northern Irkutsk District," *International Journal of Wildland Fire* 20(2), pp. 248-254.

Wierzchowski, J., Heathcott, M., and M. D. Flannigan, 2002. "Lightning and Lightning Fire, Central Cordillera, Canada," *International Journal of Wildland Fire* 11, pp. 41-51.