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Climatology of Alaskan wildfires with special emphasis on the extreme year of 2004

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Abstract Wildfires are a common experience in Alaska where, on average, 3,775 km^2 burn annually. More than 90% of the area consumed occurs in Interior Alaska, where the summers are relatively warm and dry, and the vegetation consists predominantly of spruce, birch, and cottonwood. Summers with above normal temperatures generate an increased amount of convection, resulting in more thunderstorm development and an amplified number of lightning strikes. The resulting dry conditions facilitate the spread of wildfires started by the lightning. Working with a 55-year dataset of wildfires for Alaska, an increase in the annual area burned was observed. Due to climate change, the last three decades have shown to be warmer than the previous decades. Hence, in the first 28 years of the data, two fires were observed with an area burned greater than 10,000 km^2, while there were four in the last 27 years. Correlations between the Palmer Drought Severity Index and the Canadian Drought Code, against both the number of wildfires and the area burned, gave relatively low but in some cases significant correlation values. Special emphasis is given to the fire season of 2004, in which a record of 27,200 km^2 burned. These widespread fires were due in large part to the unusual weather situation. Owing to the anticyclonic conditions of the summer of 2004, the composite anomaly of the 500 mb geopotential height showed above normal values. The dominance of a ridge pattern during summer resulted in generally clear skies, high temperatures, and below normal precipitation. Surface observations confirmed this; the summer of 2004 was the warmest and third driest for Interior Alaska in a century of climate observations. The fires lasted throughout the summer and only the snowfalls in September terminated them (at least one regenerated in spring 2005). Smoke from the forest fires affected the air quality. This could be demonstrated by measurements of visibility, fine particle matter, transmissivity of the atmosphere, and CO concentration.

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1 Introduction

Forest fires are a common occurrence during summer in Interior Alaska, which is vegetated mostly with boreal forest. Interior Alaska has a subarctic continental climate, with cold winters and relatively warm summers (Stafford et al. 2000a, b; Shulski and Wendler 2007; Wendler and Shulski 2009). The Interior is bounded to the north by the Brooks Range and to the south by the Alaska Range (Fig. 1).

In contrast, Northern Alaska has an arctic climate, the warmest month is below 10°C, and the vegetation consists of tundra. Southern Alaska is under maritime influence, hence cool and moist in summer. On average over the last 55 years, 3,775 km^2 burned annually in Alaska, which is up to ten times more area than in any other state of the USA (Court and Griffiths, 1992). Factors such as the size of Alaska, the low population density, and fire management schemes contribute to this statistic. While a significant

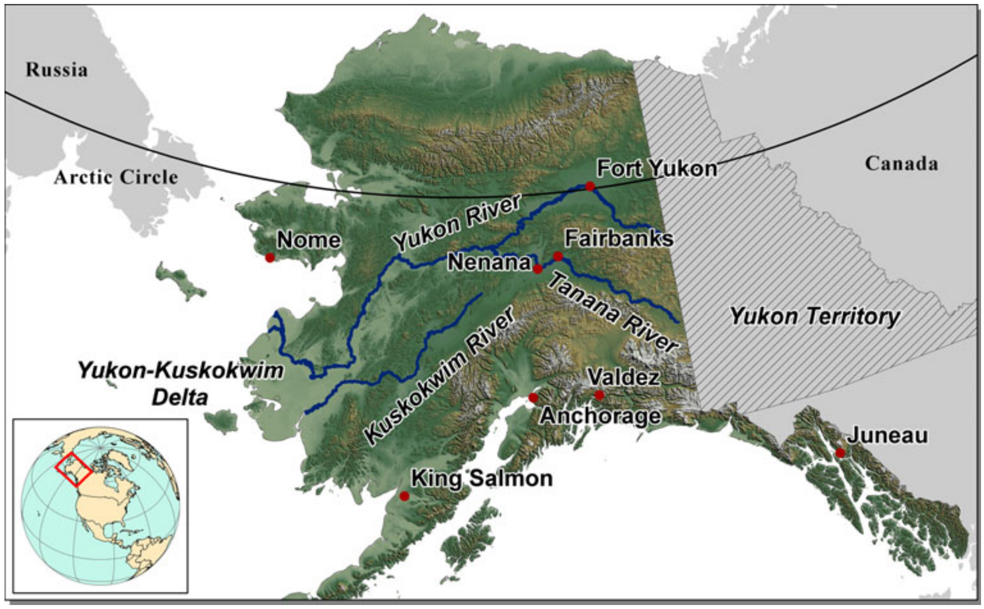


Fig. 1 Location map of Alaska

number of fires are started by human activity, 93% of the area burned in Alaska is from lightning-ignited fires.

Previous studies have investigated correlations between drought conditions and fire season severity, primarily in the western US. Pioneering work on the potential evaporation and drought conditions have been carried out by Thornwaite (1948) and later, a meteorological index of drought was developed by Palmer (1965), termed the Palmer Drought Severity Index (PDSI), which is still widely used in the USA. Alley (1984) discussed the limitations of such an index and Guttman (1991) carried out a sensitivity analysis of the index. Further, the relationship between the PDSI and wildfire season severity is discussed by Balling et al. (1992) and later by Swetnam and Betancourt (1998). Moreover, the Canadian Drought Code (CDC) was developed by Girardin et al. (2004), which, as the name indicates, is widely used in Canada.

The spatial patterns of lightning strikes in interior Alaska and their relation to elevation and vegetation were studied by Dissing (2003) and Dissing and Verbyla (2003). Rorig and Ferguson (1999, 2002) found that atmospheric sounding data can be used to help predict occurrences of "dry" versus "wet" lightning conditions, a significant factor related to wildfire starts, and McGuiney et al. (2004) investigated the relationship between lightning strikes, temperature, precipitation, and wildfires in Alaska. Skinner et al. (1999, 2001) investigated the mid-tropospheric conditions for the occurrence of large wildfires in Canada, while Duffy et al. (2005) studied the impact of atmosphere–ocean variability on Alaskan wildfires. And finally, Fauria and Johnson (2006) looked at the relationship between large-scale climatic pattern and the forest fires in Alaska and Canada. In the following, we describe the predominant weather conditions during the Alaskan fire seasons, fire characteristics, a description of the extreme 2004 fire season, and wildfire consequences in terms of air quality and visibility.

2 Lightning

Data regarding wildfires due to lightning strikes can be obtained from the Alaska Lightning Detection Network operated by the Bureau of Land Management and the Alaska Fire Service. The network has been in operation since 1986 (with an upgrade in 2000) and consists of nine stations in Alaska and three in Yukon Territory, Canada (Krider et al. 1976, 1980). If at least two stations detect a strike, the location is found by triangulation, with an accuracy of 2–4 km. Information for each strike includes latitude, longitude, time of strike, and polarity. The development of thunderstorms causing these lightning strikes can be due to either convection from surface heating or from large-scale synoptic forcing (Sullivan 1963; Biswas and Jayaweera 1976; Reap 1991). Figure 2 shows the spatial distribution of lightning strikes for a summer month (July) in Alaska. About 80% of the lightning strikes occur in Interior Alaska, where in summer the highest temperatures are observed. An indication of this can be found in the fact that the highest temperature ever observed in Alaska (100°F or 37.8°C) was at Fort Yukon, located just north of the Arctic Circle on the banks of the Yukon River. Due to long days and intense solar radiation, the atmospheric boundary layer frequently becomes unstable in the afternoon and uplift with the formation of thunderstorms will occur.

On average, there are 32,000 lightning strikes annually in Alaska. However, the variations from year to year are

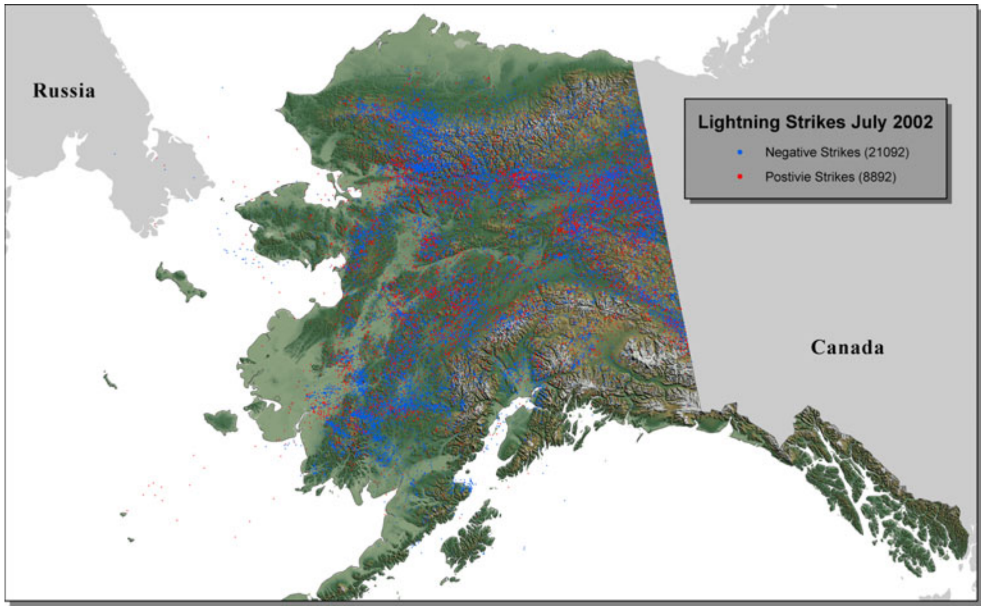


Fig. 2 Spatial distribution of lightning strikes in Alaska for a summer month (July, 2002)

large. In addition, the total strike count for a season can be strongly influenced by just a few days with a considerable number of strikes. Figure 2 also shows that a few lightning strikes have occurred over the ocean. Here, where cold ocean water prevents uplift, the strikes must have occurred along a frontal boundary. These occasions are, however, less frequent, as demonstrated in Fig. 3. Figure 3 also verifies that 99% of all lightning strikes occur from May to August. If lightning strikes were frequently caused by front-induced thunderstorms, a broader distribution over the year would be expected.

The diurnal variation of the lightning strikes in Alaska is presented in Fig. 4. It can be seen clearly that there is a very strong diurnal variation in these strikes, with a maximum of 3–4 h after solar noon and notably low values at night and early morning. This is in agreement with a previous investigation by Reap (1986) who showed, for the Western USA, a diurnal variability in the lightning strike count in which the maximum was observed from 3–6 h after solar noon. This is another strong indication that thunderstorms associated with fronts are relatively rare, as otherwise a less pronounced diurnal variation would be expected. From the daily temperature and lighting data it can be seen that for any thunderstorm activity to occur due to surface heating, the maximum daily temperature has to be above 15°C. If the temperature is below 15°C, only rarely is enough uplift generated for the formation of thunderstorms. With increasing temperature the frequency of lightning strikes increases (Table 1). On the upper extreme (maxima above 30°C), which seldom transpires, the frequency of strikes decreases again, as such high summer temperatures occur with no or few clouds, a situation normally associated with an anticyclonic system.

As such systems have a downward vertical air movement, uplift is normally suppressed. The surface absorbs a great amount of radiative energy, which is transferred into the atmospheric boundary layer both in the form of sensible and latent heat. The effects of this absorption are twofold: the surface soil layer dries out and the water content in the atmospheric boundary layer increases. After a few days, cumulus cloud development is observed during the afternoon a few hours after the maximum in solar radiation and after a few additional days, these clouds can rise high in the troposphere forming cumulonimbus clouds. This results in a somewhat reduced maximum temperature. Thunderstorms and a high number of lightning strikes are generated.

3 Wildfires

Historical fire data consisting of the total number of fires and area burned were obtained from the Alaska Fire Service for the years 1955–2009. Detailed information for the 2004 season was also obtained, which included daily summaries of fire starts, source of ignition for each fire (lightning or human), as well as the location and total area burned for each fire. From the dataset, it can be found that on average only one in about 600 lightning strikes starts a wildfire. The relationship between lightning strikes and occurrence of forest fires illustrates large variability (not shown). Statistical analyses between the number of lightning strikes and the number of wildfires started resulted in a correlation coefficient of $r=0.67$. The relationship improved substantially when the lightning strike polarity was considered. Positive strikes occur less frequently and are mostly found under dry conditions. They are, on average, four times more likely to

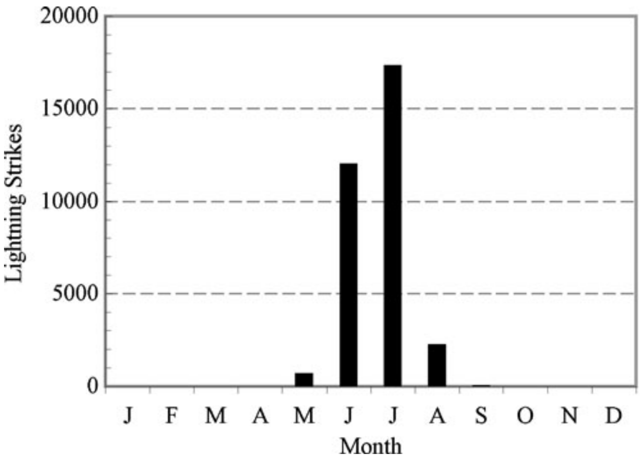


Fig. 3 Mean monthly lighting strike count for Alaska

start a fire than negative strikes, which are normally accompanied by rainfall and a wet surface, making the ignition of a fire more difficult. There is a fair amount of scatter in the relationship due to important pre-existing conditions such as the fine fuel moisture at the surface (Fig. 5).

An analyses of the historic database shows that wildfires occur mostly in June and July, the time at which the most lightning strikes were observed (Fig. 3), a result to be expected. August is the wettest month of the year for most places in Interior Alaska, and the high amount of cloudiness reduces the global radiation, surface heating, convection, and therefore the occurrence of thunderstorms. There is great variability from day to day, as well as from year to year, in the number of forest fires started.

In Fig. 6, the number of fires and the area burned per season in Alaska since 1955 are presented for an annual basis. On average, there are about 471 fires that occur in a season. In general, there is some relationship between the number of fires and the area burned; however, the relationship is weak. For example, the worst fire season that was ever recorded in Alaska (2004) consisted of 640 fires, which is an above normal but not an extreme value.

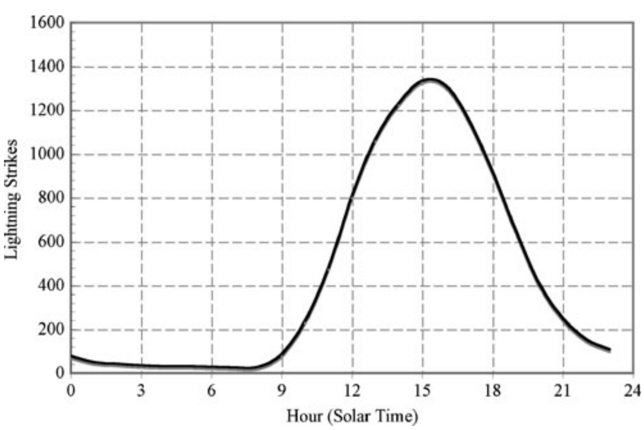


Fig. 4 Diurnal variations in lightning strike frequency

Six years in the time series have a higher fire count and six additional years show similar values. This demonstrates that it is not only the number of fires started, but also the spreading of the fires is of importance for an extreme fire season. Human interaction plays a major role in this, as efforts in wildfire suppression depend on the location.

A contributing factor to the size of a fire can be the location of its origin. There are four different protection levels in use in Alaska: critical, full, modified, and limited. Normally, fires close to population centers are fought more intensely than those in the more remote areas of Alaska. A distinctive example can be found in the occurrence of the Boundary Fire of 2004, which started just outside of the North Star Borough (the county level government surrounding Fairbanks in Central Alaska). As wildfires outside of the Borough are not fought with the same ferocity as those that are within the Borough, the fire grew rapidly, spread, and crossed the Borough boundary. However, by the time the fire entered the Borough, it was so large and intense (see Fig. 12) that enhanced firefighting efforts could not suppress it. Further, the count and area burned numbers include those fires caused by human action, which are normally nearer to population centers and fought more rapidly and intensely. On average, less than 10% of the area burned is due to these types of fires. In 2004, an area of 27,200 km^2 burned, an area seven times the normal value and larger than the size of any of the seven smallest states in the USA.

4 Climate–wildfire relations

The Palmer Drought Severity Index is frequently used as an indicator of the fire danger and it is based on temperature and precipitation. We calculated these values for the 55 years for which we have wildfire information for Alaska (1955–2009). The mean monthly temperature and precipitation data for Fairbanks were used as input to represent the continental climate of Interior Alaska. Generally, valley locations in Interior Alaska have a fairly uniform climate (Wendler and Shulski 2009), however, the soil conditions vary widely and large areas of Alaska are underlain with permafrost, changing the surface hydrology substantially. Permafrost underlain areas are not permeable to water, and the soil hydrology is limited to the active layer, which is the

Table 1 Lightning strike frequency as function of the maximum daily temperature for strikes within ±0.5° of Fairbanks for years 1984–2003

Max daily temp (°C)	10–15	16–20	21–25	26–30	>30
Strike frequency	0.2	6.9	21.2	44.4	13.0

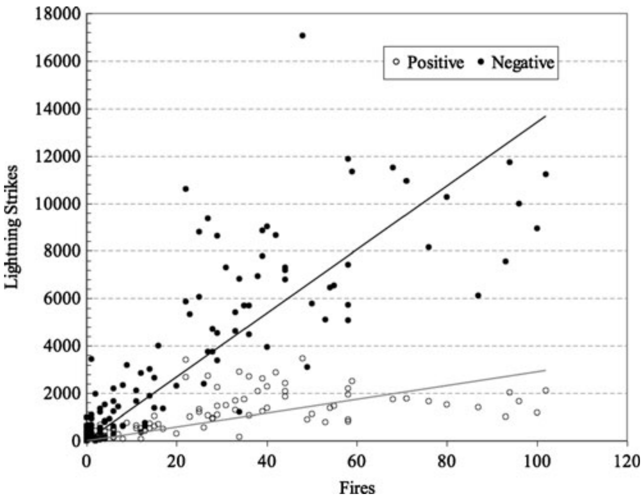


Fig. 5 Number of wildfires vs. positive and negative strike count (1984–2004)

layer that thaws in summer, and is typically 0.5–1.5 m deep. Much of Interior Alaska is an area of discontinuous permafrost: south-facing slopes and large water channels are normally free of permafrost, while on northern slopes permafrost is normally present. Black spruce is a typical indicator of the presence of permafrost. Because of these soil discontinuities, calculations were carried out with three different values for the available water capacity (AWC) of soil, 40, 60, and 80 mm. These calculations were performed on a by monthly basis, spring and summer combined, and summer. Finally, these values were correlated with the number of fires, as well as with the area burned. In Table 2, the correlation coefficients of the PDSI for summer months against both the number of fires and area burned are given. Only summer is shown as it provided somewhat higher correlation coefficients than spring, summer and spring combined, or any single month. As the agreement found for the PDSI is fairly poor, we calculated the relationships with the Canadian Drought Code, an index more frequently used in Canada (Girardin et al. 2004). The CDC is a slow-drying index with a time lag of 52 days (Turner 1972). As input, we used the Fairbanks's temperature and precipitation data. We calculated correlations for monthly as well as longer seasonal time frames. The monthly correlation coefficients were slightly lower than the seasonal values, some of which are presented in Table 2. Nevertheless, the relationships are marginally stronger than those found for the PDSI.

In Fig. 7, a graph of the CDC against the number of fires is presented for the summer months (May–September). The relationship is fairly weak with a correlation coefficient of 0.35.

5 Weather of 2004

Predictions made during the spring of 2004 for the upcoming fire season called for above normal fire danger for only a portion of the Yukon-Kuskokwim Delta region in southwest Alaska. This was due to below normal spring-

Fig. 6 Number of fire observed in Alaska per year and area burned from 1955 to 2009

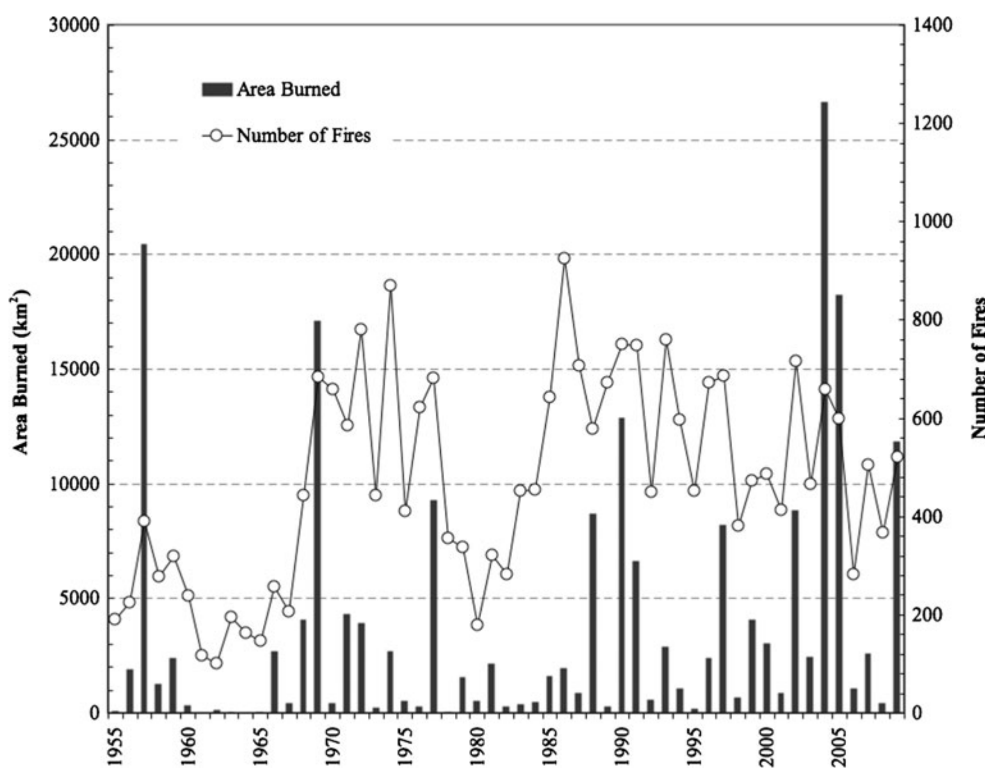


Table 2 Correlation coefficients of the Palmer Drought Severity Index (PDSI) and Canadian Drought Code against the number of fires started and the area burned, respectively, for 1955–2009

	Number of fires	Area burned
Palmer Drought Severity Index		
AWC		
40	−0.10	−0.08
60	−0.21	−0.06
80	−0.26	−0.08
Canadian Drought Code		
Time frame		
Breakup–August	0.23	0.13
April–October	0.32	0.30
August	0.34	0.28
May–August	0.35	0.22
May–September	0.35	0.28

The calculations were carried out for different available water capacity (AWC) of soils for the PDSI and for different time frames for the CDC. The climate data for the CDC were based on Fairbanks

time snow-pack conditions in this region, along with warmer than normal temperature predictions for the time period after snowmelt and before green-up, a critical time in the Interior Alaska fire season. In addition, climate predictions gave little or no guidance as to the abnormally warm and dry summer weather experienced in 2004 that eventually led to the extreme fire season.

After the 2004 snowmelt, which occurred in late April, May was warmer and wetter than ordinary. In fact, Fairbanks had the wettest May on record. However, the three following months were under the influence of a semi-permanent high-pressure ridge, located in eastern Interior Alaska/western Yukon Territory, bringing above normal temperatures and below normal precipitation. A detailed description of the weather of summer 2004 is given by Richmond and Shy (2005). In Fig. 8, the anomaly of the 500 hPa geopotential height from the long-term mean is presented for the summer of 2004. Strong positive deviations in the order of 70 m are shown centrally located over Alaska. This also explains the fairly widespread and uniform deviations in temperature and precipitation. In Table 3, the temperature and precipitation data of Fairbanks for the summer months of 2004 are presented.

Table 3 shows that the temperature in Fairbanks was unusually high during the summer of 2004; a deviation of 2.9°C was observed for the mean of the summer, and in June, at the start of the fire season, a deviation of 4.0°C materialized. It represented the highest summer temperature ever measured in Fairbanks, which has a dataset spanning over 100 years. Other regions in Alaska were also warmer than normal. For example, Nome, King Salmon, Anchorage, Valdez, and Juneau all recorded new record high summer temperatures in 2004. Fairbanks precipitation measurements revealed a 78-mm deficit. This might not appear to be a hefty amount at first glance, but precipitation is light in Interior Alaska (123 mm on average for an entire summer), and the amount received represents only 37% of normal precipitation, and is the third lowest value of rainfall ever observed during a Fairbanks summer.

The question arises how representative is Fairbanks for Interior Alaska. As previously mentioned, and shown in the literature, the climate of the low-elevation areas of the Yukon and Tanana watersheds are fairly uniform. Figure 9 shows the cumulative temperature departure from the 30-year norm for Fairbanks and Nenana; the two sites are 80 km apart from each other. Strong temperature deviation gradients were observed especially during the second half of June and the first half of August. In late August, the temperature was normal or slightly below the 30-year mean.

Precipitation is, of course, more variable spatially than temperature as it is strongly affected in summer by localized thundershowers. Fairbanks recorded a precipitation deficit for the summer of 2004 of 63%, while the deficit for Nenana, 80 km southwest of Fairbanks, was 29%.

6 Wildfires of 2004

It has previously been noted that in summer 2004 there was an increased number of fires, and fire spread was more pronounced. By the end of June, a large number of forest fires were burning in Alaska (Fig. 10).

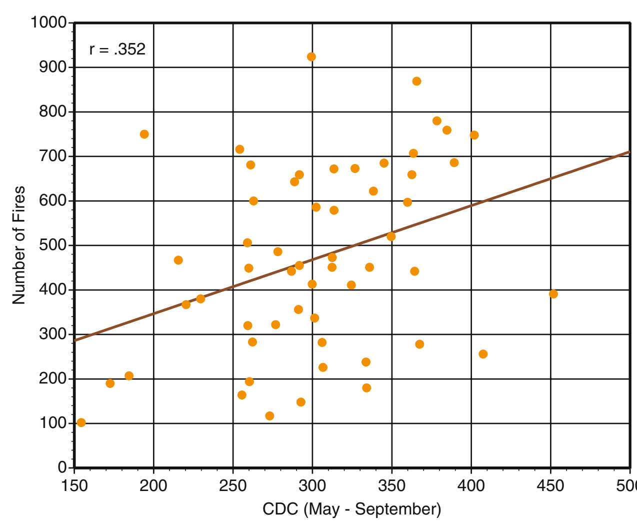
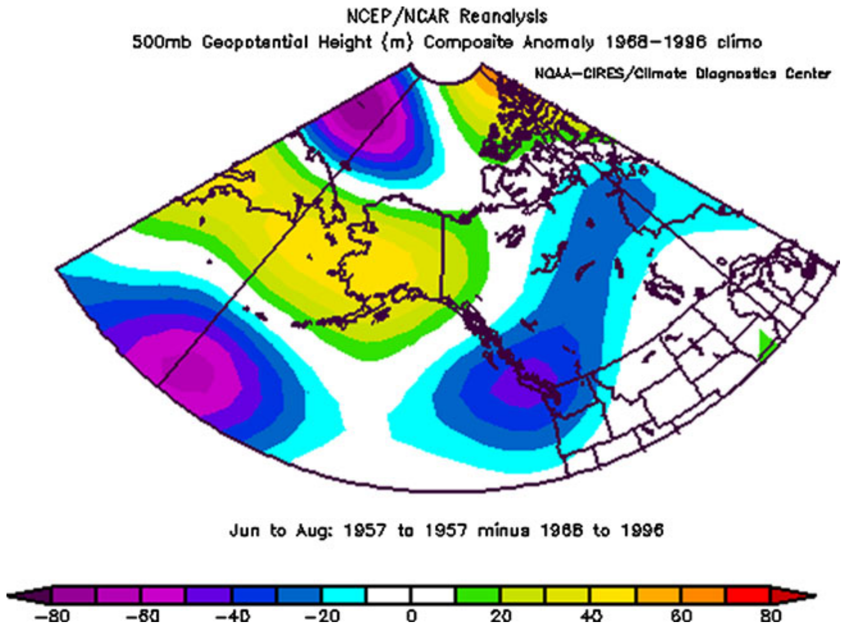


Fig. 7 The Canadian Drought Code (CDC) against the number of fires started for the time period 1955–2009

Fig. 8 Anomaly of the 500 hPa geopotential height (m) from the long-term mean for the summer of 2004, based on the NCEP/NCAR reanalysis



In Fig. 11, the number of active fires and a cumulative total of the area burned are presented. The number of active fires was low with 16 until 10 June, then a sharp increase occurred, and by 15 June, 58 fires were active throughout the state. Up to the middle of July the number of fires increased only slightly, but thereafter a second strong increase occurred and by 21 July, 114 fires were burning. Throughout August the number of active fires stayed high with values around 100, and then towards the end of September a strong decrease materialized as would be expected with the onset of the subarctic winter.

The existing wildfires were spreading fast after the middle of June (Fig. 12), and while the number increased only slightly, a total of about 16,200 km^2 burned over the following 4 weeks (some 600 km^2 daily). The fires were intense (Fig. 10), and firefighting efforts were not particularly effective. A break in the weather helped the fire fighters toward the end of July with widespread rain, the first substantial precipitation in Interior Alaska since the beginning of June. The fires started to flare up again on 10 August and during the next 3 weeks an additional 8,000 km^2 burned. During this period the number of active fires stayed fairly constant. Note that the rate of burning is only half of the value recorded earlier in the summer. While quite a number of fires continued smoldering in September, little additional area was burned (Fig. 11).

7 Visibility

From late June throughout July, August, and into September, most of interior Alaska was under a blanket of smoke, the intensity of which varied with time and place. In Fig. 13, the visibility, which can be taken as an indication of the smoke intensity in the absence of fog, is presented for two interior cities, Fairbanks and Nenana, the latter being located 80 km down the Tanana River from Fairbanks. In general, the visibility limitations for Fairbanks and Nenana are quite similar, with the exception of the first severe onset in Fairbanks on 28 June, appearing in Nenana later. The good agreement can be taken as an indication that the smoke was widespread, which could have been already deduced from the

Table 3 Temperature and precipitation of Fairbanks during the summer of 2004

Month	*T* mean	*T* observed 2004	Δ *T* 2004	*P* mean	*P* observed 2004	Δ *P* 2004
June	15.4	19.4	4.0	36	8	−28
July	16.9	18.1	1.2	44	29	−15
August	13.4	17.0	3.6	44	9	−35
Summer	15.2	18.1	2.9	124	46	−78

T temperature (°C), *P* precipitation (mm), *T* (mean), and *P* (mean) is the average temperature or precipitation, respectively, for the last 30-year normal, 1971–2000; Δ is the deviation from the mean

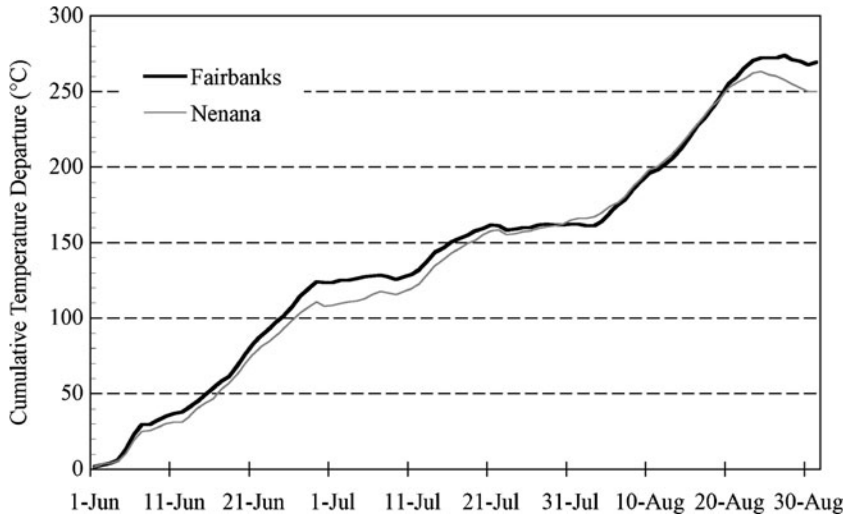


Fig. 9 Cumulative mean daily temperature departures for Fairbanks and Nenana from 1 June to 31 August 2004

satellite image (Fig. 10). The visibility is continuously measured at the respective airports with an automatic device (part of the Automatic Surface Observing System). The system employs a Belfort Model 6220 forward scatter visibility meter, from which the Sensor Equivalent Visibility is derived. The observation range of the instrument is from <1/4 mile to >10 miles.[1] Bradley and Imbembo (1985) give a detailed description of the instrument. A further restriction of the device is that visibilities above 10 miles cannot be resolved; and generally the visibility in Interior Alaska is quite good, with the Alaska Range, some 100 km south of Fairbanks, frequently visible from Fairbanks. In the graph (Fig. 13), the hourly visibility observations were averaged and daily mean values are presented. Two obvious periods of extreme visibility reductions were experienced with values dipping to less than 1/4 mile (400 m), between 27 June–4 July and 16–30 August. Air traffic was suspended for both periods, cars were driven with headlights on, outdoor activities and sporting events were canceled, and the population was advised to stay inside.

We focus our discussion on the first period for the Fairbanks location, during which we have visibility, particulate matter, CO concentration, and radiative fluxes data. The two periods were similar, with the exception in that the first one was cloud free for the entire period from 23 June to 3 July, while some clouds occurred during the second, longer (15 day) period.

We carry out continuous radiative measurements on the roof of the Geophysical Institute of the University of Alaska, Fairbanks. In Table 4 the mean radiative fluxes are presented. The table shows that the direct beam radiation on average was reduced by 89.6%. We also carried out actinometer spot measurements with broad-spectrum filters, which gave in part even higher values. They also showed that the shorter wavelengths (blue) were reduced to a larger extent than the longer wavelengths (red); this is not a surprising result, as the solar disk has a red/brownish color under smoky conditions. Applying the Bouguer-Lambert law, we can determine the optical depth. From values close to solar noon, we found 0.34 for clear conditions and 1.82 after the arrival of the smoke. The global radiation is reduced by nearly 60% on average; however, losses in the direct beam radiation are in part compensated by an increase in the diffuse radiation, which nearly doubled. Before the smoke arrived, the diffuse radiation contributed 16% to the global radiation, but after the arrival of the smoke, it contributed 76%. About 20% of the direct beam is forward scattered by the smoke, while the rest is either absorbed by the smoke or reflected back to space. The ultraviolet measurements (UV-A and UV-B) show an even a more pronounced depletion rate than the visible spectrum. Little, if any, UV radiation was measured at the surface within the smoke. This result is not unexpected as our spectral spot measurements already showed this trend. Due to the relatively large size of smoke particles, they absorb a higher percentage of the shorter wavelength's radiation instead of scattering it (Table 4).

8 Particle matter and CO-concentration

The particle matter with aerodynamic sizes smaller than 2.5 μm (PM 2.5) was measured on top of the Fairbanks Regional Office Building in downtown Fairbanks. Hourly data were collected with a MetOne BAM 1020 sampler (**B**eta **A**ttenuation **M**onitor). Data compilation was started midsummer 2003. A beta attenuation process is applied to determine the mass collected on a filter tape as calibrated

[1] As these measurements are carried out in miles, we intentionally did not convert them into metric units (1 mile=1.609 km).

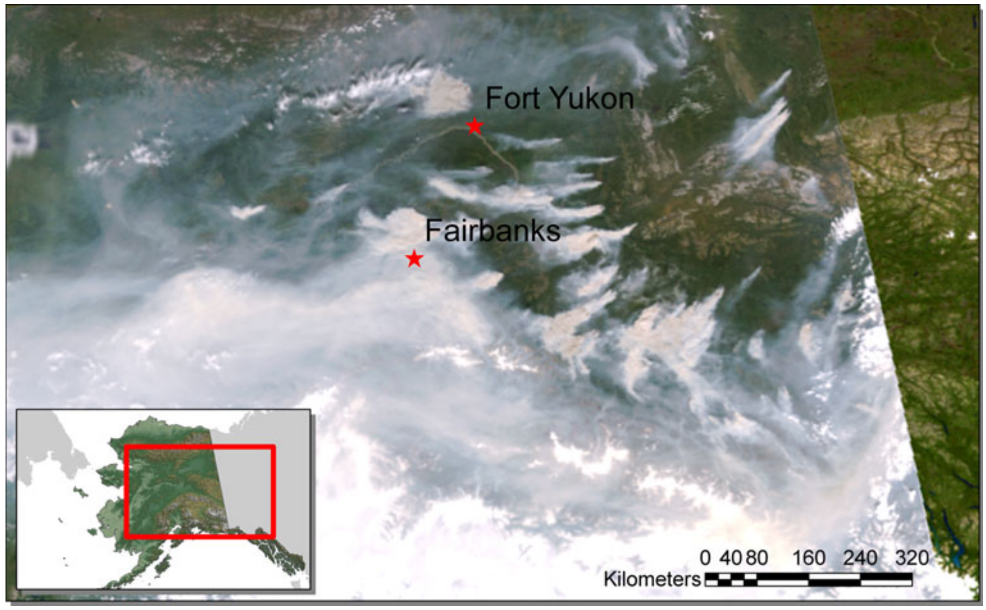


Fig. 10 Visible satellite image from MODIS of Central Alaska and Yukon Territory, taken on 29 June 2004. Image courtesy of the Geographic Information Network of Alaska (GINA), University of Alaska

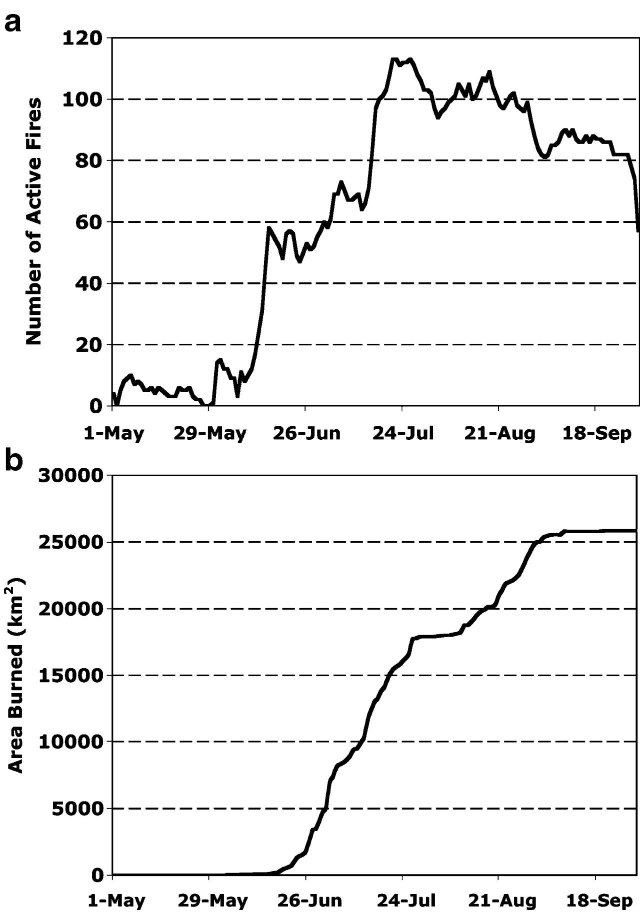


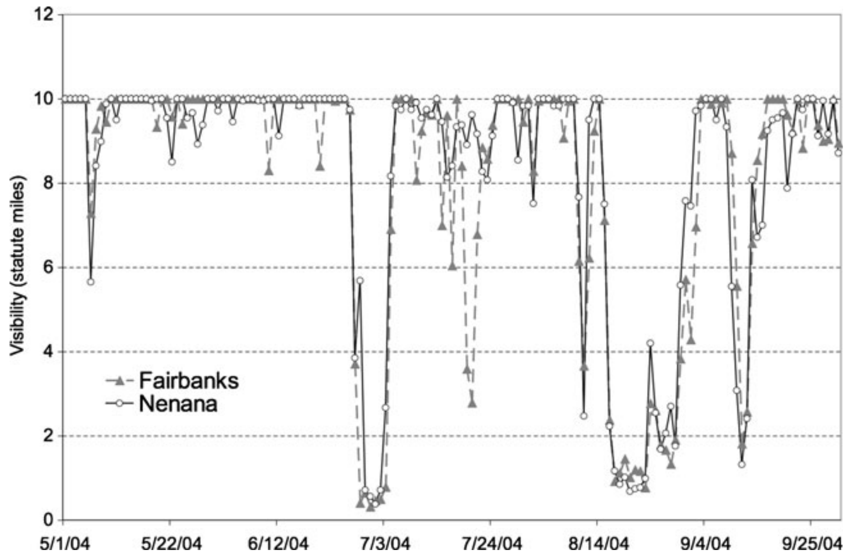
Fig. 11 Daily number of active fires (**a**) and cumulative total area burned (**b**) in Alaska for the period 1 May to 30 September 2004

airflow passes through the tape. The beta radiation attenuation is compared before and after collection within the instrument. The accuracy of the instrument is ±7 μg/m^3.

Carbon monoxide (CO) measurements were performed during summer at a single location in downtown Fairbanks, approximately 1/2 mile from the particle samplers. The instrument deployed is an Environmental Corporation Dasibi Model 3008 CO Analyzer. It is based on the Gas Filter Correlation technique and has an accuracy of ±0.5 ppm. The Clean Air Act established health-based National Ambient Air Quality Standards (NAAQS) for pollutants. Based on the NAAQS, the EPA established air quality categories with specific health cautions for each range. To avoid a violation of the EPA set standard, the ambient anthropogenic CO must not exceed 9 ppm for an 8-h average and 35 ppm for an hourly

Fig. 12 Photo of the Boundary Fire off the Steese Highway north of Fairbanks taken summer 2004, Alaska Fire Service. Note that spruce tree fires can be quite explosive

Fig. 13 Time series of average daily visibility observations at Fairbanks and Nenana for the period 1 May to 30 September 2004



value. Due to the ±0.5 ppm accuracy of the instruments, we are allowed to exceed these standards by up to 0.5 ppm. Concerning the fine particle matter, PM 2.5, the daily values should stay below 65 μg/m^3 and the annual value should not surpass 15 μg/m^3.

Figure 14 shows (a) CO concentration, (b) fine particle, as well as the transmissivity of the direct solar beam (c) for the time frame from 23 June to 8 July. It can be seen that on 27 June, strong northerly winds advected heavy smoke into Fairbanks from the Boundary Fire, situated north of Fairbanks. An inversion during the night hindered vertical mixing, and at 0200 hours on 28 June, a CO concentration of 10.3 ppm was recorded, resulting in an 8-h average concentration of 9.2 ppm. By 1000 hours the 8-hourly averaged CO concentration had dropped to 8.6 ppm, and never again approached the reference violation level. This was a summer record high value for Fairbanks. For example, the maximum for summer 2003, including smoke events from forest fires in the area, was 3.5 ppm. The extreme value observed in 2004 is more typical for winters when, due to a strong and semi-permanent inversion (Wendler and Nicpon 1975), the boundary layer is separated from the air aloft. The figure shows also a small systematic diurnal variation in CO for the time before the smoke arrived, with a maximum of about 1 ppm during the daytime. This is caused by automobile traffic emissions in Fairbanks. As stated previously, the measurements were performed in downtown Fairbanks. This periodicity is less visible after the arrival of the smoke, as much CO concentrations due to nearby wildfires are more pronounced than small diurnal variation due to road traffic.

Fine particle matter (Fig. 14b) exceeded 1,000 μg/m^3 at about at the same time as the CO reached its maximum. In the early morning hours of the 28 June, the sensor became saturated, and measurements remained off scale for the next 8 h. The steep decrease from the peak in particle matter is somewhat delayed when compared to the CO track. The maximum surpassed the most dangerous EPA standard (hazardous) by a factor of two. This was an extraordinary event as no previous observations have recorded such elevated values in Fairbanks. Health concerns were very serious, warnings were issued and the sick and elderly were advised to stay inside their apartments. Figure 15 shows a photo taken in front of the Geophysical Institute, University of Alaska (our radiation station is located on the roof of the building to the left of the photo). The normal summer average for PM 2.5, including short-lived wildfire smoke, is 7 μg/m^3 for Fairbanks.

Table 4 Mean radiative fluxes for the mean of 7 h centered on solar noon before major smoke arrived in Fairbanks (23–27 June 2004) as compared to the days Fairbanks was under a heavy blanket of smoke (28 June–3 July 2004)

Radiation component	23–27 June (W/m^2)	28 June–3July (W/m^2)	Difference (W/m^2)	Difference (%)
Direct beam	683	71	−612	−89.6
Global	531	225	−306	−57.6
Diffuse	86	170	+84	+97.7
UV-A	9.8	0.7	−9.1	−92.9
UV-B	0.45	0.01	−0.44	−97.8
IR	343	348	+5	+1.5

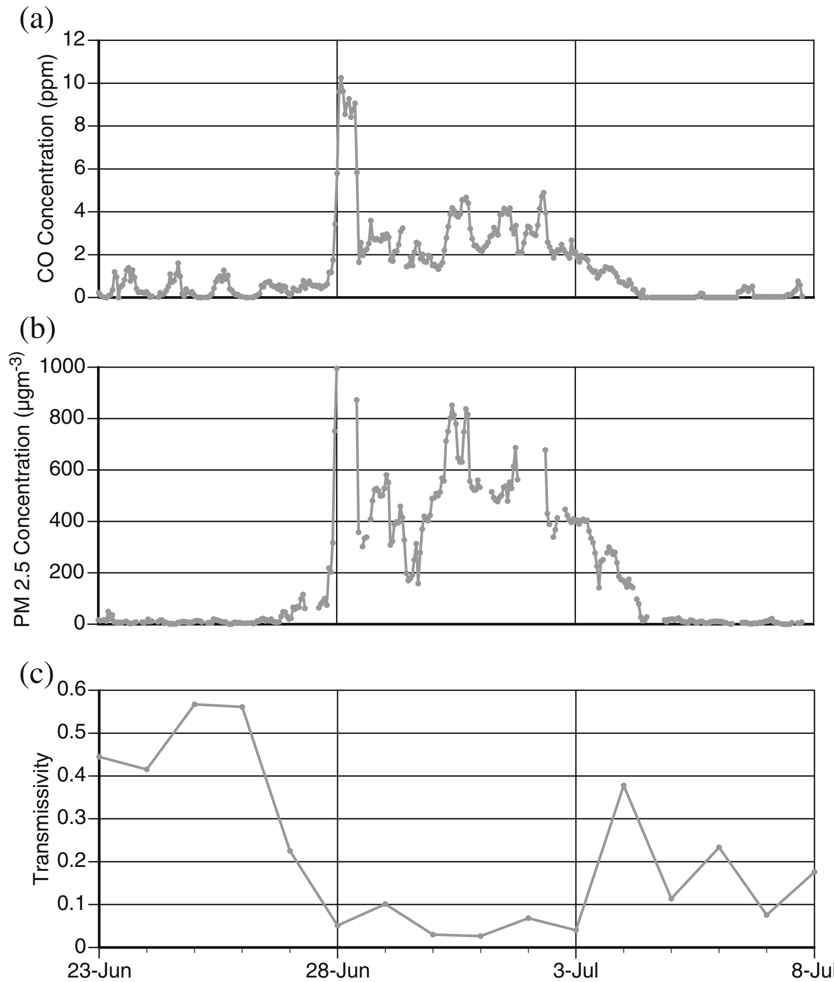


Fig. 14 Time series of (a) CO concentration, (b) fine particle matter (PM 2.5), and (c) transmissivity at Fairbanks for the period 23 June to 8 July 2004

Fig. 15 Smoke as seen in front of the Geophysical Institute, University of Alaska during summer, 2004. On the roof of the building is where the radiation array is located

The transmissivity (Fig. 14c) was calculated as the percentage of the solar radiation outside of the atmosphere that reached the surface as direct radiation. These numbers were calculated as a mean of the 7-hourly values around solar noon. While about 1/2 of the direct solar beam reached the surface as direct radiation before the major smoke event, less than 10% were measured within the smoke.

We correlated the CO and fine particle matter concentrations for the two extreme events. The variance between the two variables is relatively high, with 72% in the first period (1 June–15 July) and 80% in the second period (16 July–31 August). Furthermore, while the absolute values were smaller for CO during the second period, the relative CO abundance against the fine particle concentration was higher by nearly one quarter. For CO the average lifetime is some 3 months. The lifetime of fine particles is notably less, as they are removed by fall out and wash out. Therefore, it can be concluded that a relative abundance of CO in relation to particle matter is to be expected for the older smoke of the second period. Light extinction within a turbid medium such as smoke will depend on the path-

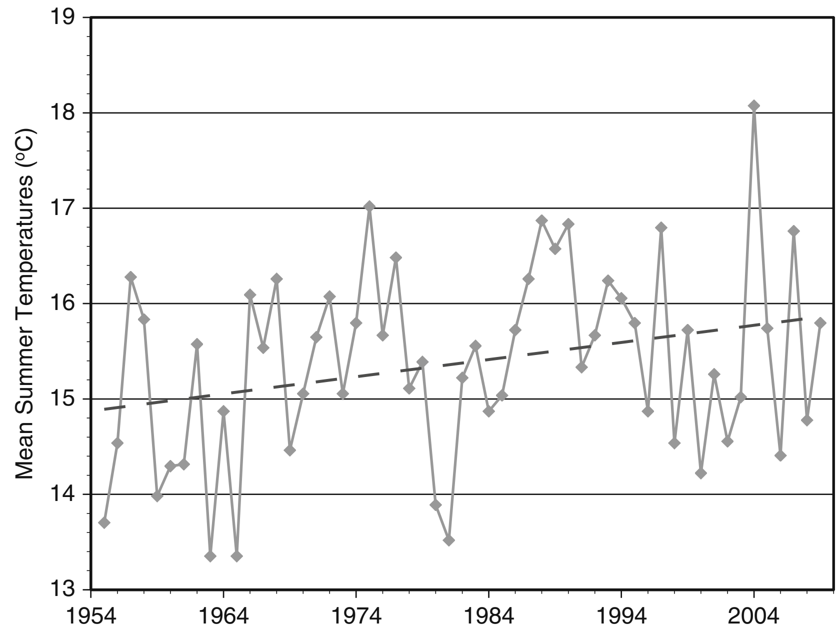


Fig. 16 Summer temperatures (June, July, August) from 1955–2009

length through the medium. The condition for this is, of course, that the medium be fairly uniform. The good agreement (Fig. 9) between Fairbanks and Nenana verifies the uniformity of the smoke particles. However, the PM 2.5 gives only the weight of all particles smaller than 2.5 μm, and does not give information on the size distribution of the particles. As one large particle of 2.5 μm will have 1,000 times the mass of a particle of 0.25 μm, both absorption and scattering will depend on the size distribution. Therefore, the relationship of the logarithm of the visibility against PM 2.5 concentration was not great (not shown). Furthermore, there is the fact that particles larger than 2.5 μm are not measured at all, while still having an effect on the visibility. Such large particles are also present in wildfire smoke as shown by Eaton and Wendler (1983).

9 Outlook and conclusion

A recent study has shown that the Interior Alaska has experienced a temperature increase over the last century (Wendler and Shulski 2009). The increase for the summer months since 1955 is shown in Fig. 16. The increase was 1°C over the last 55 years, a larger amount than seen worldwide,

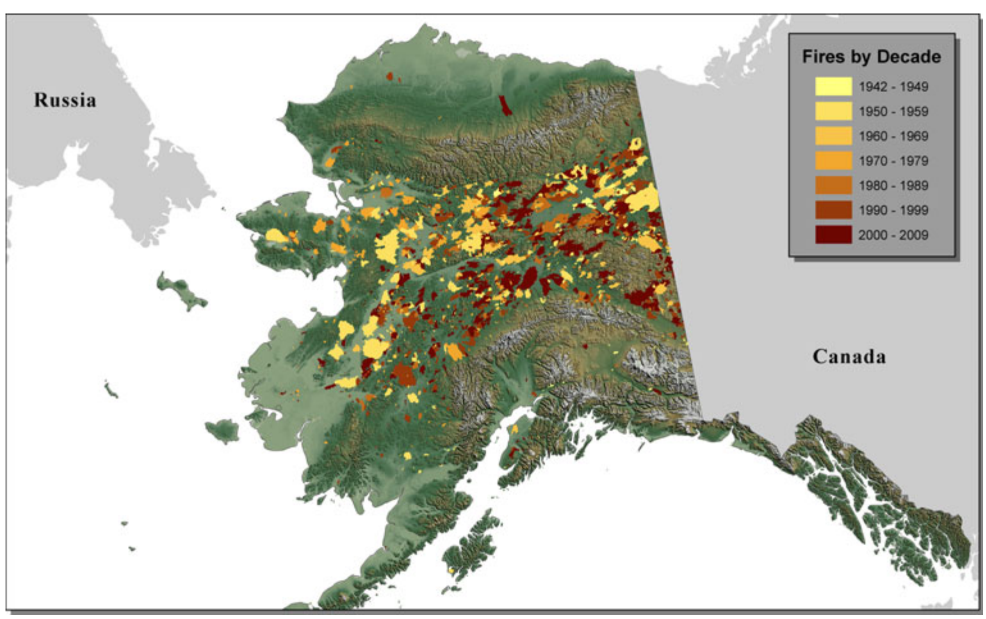


Fig. 17 Area burned in Alaska over more than the last half century. Note that very large portion of the Interior of Alaska has been affected

but expected due to the so-called polar amplification projected with global climate change. In the first half of the observational period, there are 6 years with mean summer temperatures above 16°C, while for the second half, there were nine such events. Higher temperatures lead to warmer and drier surface conditions, increasing the probability of a lightning strike to start a fire. Furthermore, the spreading of fires is facilitated under dry soil and fine fuel conditions. The area burned varies widely from year to year, but has increased on average over the last 55 years, even though more effective fire fighting techniques have been developed. Very large fire seasons (>10,000 km^2 burned) increased from 2 to 4 events from the first half to the second half of the observational period, while large ones (>5,000 km^2 burned) increased from three to eight events (Fig. 6).

In the study noted above for analyzing the climate change over a century for Fairbanks (Wendler and Shulski 2009), showed not only a temperature increase of 1.4°C, but in addition a precipitation decrease of 11%, leading to both drier and warmer conditions. In addition, the length of the growing season—that is the time period when the temperature in summer stays continuously above the freezing point—increased by 45% over the century, indeed a considerable change, leading to a more active biota and tree growth. Additionally, this warming will lead to melting of the permafrost, where currently mostly black spruce, sparsely spaced, is present. Other vegetation types such as white spruce might replace black spruce, consisting of larger trees and a more dense growth. Such changes in vegetation will have an effect on the future area burned by wildfires.

On the other hand, given the large area that has burned over the last half century in Interior Alaska (Fig. 17), there will be less old growth forested area (which is especially susceptible to fires) available for any year going forward. This decrease in venerable fuel might balance the expected temperature increase and precipitation decrease. Further, it is worth noting that while in Alaska firefighting efforts are substantial, monetarily, less than 10% is spent for every acre burned when compared to the contiguous US states.

Finally, improvement in forecasting the coming fire season would be helpful for anticipating the required effort in fire fighting required for any 1 year. Regrettably, the seasonal forecast for Alaska has no skill, as it consist simply of the mean of the last 30-year climate period. Bienniek (2007) applied multiple regression analyses between the preseason air temperatures as well as the 500 hPa geopotential heights based on pre-seasonal data and the size of the area burned. He found promising results between the predicted and actual burned area (r=0.92), but only the future will show the practical value of this technique.

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