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A 1000-yr record of forest fire activity from Eclipse Icefield, Yukon, Canada

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Abstract: A 1000-yr record of forest fire activity has been developed using three annually dated ice cores from Eclipse Icefield, Yukon, Canada. Forest fire signals were identified as NH_4^+ residuals above a robust spline and corroborated by an empirical orthhogonal function (EOF) analysis that identified a chemical association in the NH_4^+, $C_2O_4^{2-}$ and K^+ records similar to that observed in forest fire plumes. These statistical techniques yielded similar records of forest fire activity, although the EOF analysis provides more conservative identification of forest fire signals. Comparison of forest fire signals in the Eclipse ice cores with the record of annual area burned in Alaska and the Yukon demonstrates that 80% of high fire years in Alaska and 79% of high fire years in the Yukon are identifiable as NH_4^+ concentration residuals in at least one core from Eclipse Icefield, although any individual core records 36–67% of these events. The Eclipse ice cores record high fire activity in the AD 1760s, 1780s, 1840s, 1860s, 1880s, 1890s, 1920s–1940s and 1980s. Peak fire activity occurred in the 1890s, possibly reflecting anthropogenic ignition sources associated with the large influx of people to the Yukon during the Klondike Gold Rush. Periods of low fire activity are evident during the 1770s, 1810s–1830s, 1850s, 1950s and 1960s. Extending our proxy of fire activity to AD 1000 using annual NH_4^+ concentrations from our one core that extends back this far provides evidence of high fire activity from 1240 to 1410 during the waning stages of the 'Mediaeval Warm Period'.

Key words: Alaska, fire history, forest fires, ice cores, late Holocene, 'Mediaeval Warm Period', Yukon, Canada.

Introduction

The occurrence of fire in the boreal forest is highly variable from year to year, responding largely to climatic variations. Strong correlations have been reported between annual area burned by forest fires in Alaska and both temperature and precipitation, with greater areas burned in warmer and drier years (Kasischke *et al.*, 2002). Relationships have also been demonstrated between annual area burned and indices of atmospheric circulation such as the El Niño–Southern Oscillation and Pacific Decadal Oscillation, which exert considerable influence on temperature and precipitation anomalies in Alaska (Heyerdahl *et al.*, 2002). In fact, annual area burned statistics demonstrate that 15 of the 17 largest fire years in Alaska since 1940 occurred during or just after El Niño conditions, which in interior Alaska are accompanied by slightly warmer but significantly drier conditions (Hess *et al.*, 2001). Area burned statistics in Canada and Alaska are also well correlated with lightning frequency, relative humidity and 500 hPa height anomalies (Flannigan and Harrington, 1988; Skinner *et al.*, 1999, 2002; Kasischke *et al.*, 2002). The sensitivity of high northern latitudes to projected climatic changes over the twenty-first century is expected to result in a significant increase in forest fire activity in the boreal forest as a result of higher summer temperatures and lengthened fire seasons (Wotton and Flannigan, 1993; Stocks *et al.*, 1998). In fact, anthropogenic climate change may be responsible for the increase in annual area burned by wildfire in Canada since 1970 (Gillett *et al.*, 2004). Long-term records of boreal forest fire activity are needed to evaluate the response of boreal fire regimes to climate change.

Since the boreal forest is an important carbon sink, boreal forest fires also have important implications for the global carbon cycle (eg, Kasischke *et al.*, 2005). In fact, forest fires in the boreal region of Alaska alone can release as much as

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36 teragrams (Tg, 10^{12} g) of carbon to the atmosphere, mostly as CO_2, in a single high-fire year such as 1990 (French *et al.*, 2003). Furthermore, forest fires emit large quantities of aerosols, reactive trace gases and black carbon soot, all of which play important roles in atmospheric chemistry, regional air quality and climate (Levine, 1991; DeBell *et al.*, 2004). For example, carbon monoxide and methane from forest fires reduce the oxidative capacity of the atmosphere by reacting with hydroxyl radical (Crutzen and Andreae, 1990). Nitrogen oxides and hydrocarbons from forest fires participate in tropospheric ozone-forming reactions, altering the oxidation pathways of sulphur and nitrogen species (Alexander *et al.*, 2004). Particulate organic carbon in forest fire smoke can act as cloud condensation nuclei, affecting cloud microphysical and optical properties and altering the radiation budget and hydrologic cycle (Penner *et al.*, 1992).

Forest fire plumes also contain large enhancements of aerosol NH_4^+, NO_3^-, excess fine K^+ and various organic acids such as oxalate, acetate and formate (Lefer *et al.*, 1994). In fact, forest fires may be the dominant source of NH_4^+ in the Arctic and Subarctic free troposphere during summer (Talbot *et al.*, 1992). Forest fires are estimated to contribute between 10% and 40% of the total NH_4^+ deposited on the Greenland Ice Sheet during the Holocene (Fuhrer *et al.*, 1996) and 20% to 30% of total oxalate deposition (Legrand and De Angelis, 1996). Increased concentrations of these species in glacial ice reflect passage of a forest fire plume over a site while snowfall occurred, allowing the use of ice core records in reconstructing forest fire activity (Legrand and De Angelis, 1992, 1996; Whitlow *et al.*, 1994; Fuhrer *et al.*, 1996; Fuhrer and Legrand, 1997; Savarino and Legrand, 1998). Abrupt, short-duration decreases in ice core electrical conductivity (ECM) resulting from NH_4^+ neutralization of acids present in the ice can also be used to detect forest fire signals in ice cores (Taylor *et al.*, 1996). Other archives of palaeoforest fire activity include fire-scarred tree rings (eg, Larsen, 1997) and charcoal abundance in lake sediments (eg, Lynch *et al.*, 2004).

For a forest fire signal to be recorded in glacial ice, meteorological conditions must be favourable for transport of the plume from the fire to the ice core site, loss by scavenging during atmospheric transport must be minimal, wet and/or dry depositional processes must transfer the atmospheric signal to the surface snow and the labelled snow must be preserved in the ice core (Whitlow *et al.*, 1994; Slater *et al.*, 2001). Since biomass-burning plumes are chemically heterogeneous and depositional processes and post-depositional alteration can produce considerable spatial variability in glaciochemical signals, there is not, nor should one expect, a one-to-one relationship between forest fires in the source region and detectable forest fire signals in ice core NH_4^+, K^+, organic acids and ECM records. Furthermore, it is not possible to accurately determine the magnitude of a given forest fire event from ice core chemical concentrations because of variable transport distances and meteorological conditions. Instead, ice cores provide a more general record of relative fire activity in upwind regions (Whitlow *et al.*, 1994). Although NH_4^+ in polar snow and ice has other sources such as emissions from vegetation and soil microbial activity (eg, Meeker *et al.*, 1997), large, short-term increases in ammonium are uniquely associated with forest fires (Taylor *et al.*, 1996). Oxalate is produced only by combustion processes (Lefer *et al.*, 1994); potentially offering corroboration of ice core NH_4^+ signals thought to represent forest fires. Meanwhile, peaks in non-sea-salt K^+ can be associated with crustal dust, making K^+ an ambiguous tracer of forest fires (Legrand and De Angelis, 1996). Attributing NO_3^- concentration peaks in snow solely to forest fires is also problematic because of the multitude of nitrate sources and post-depositional alteration of nitrate signals via photochemical recycling (Dibb *et al.*, 2002).

Studies of Greenland ice cores suggest they preserve a record of forest fire activity in North America, particularly eastern Canada (Legrand and De Angelis, 1992, 1996; Whitlow *et al.*, 1994; Taylor *et al.*, 1996). In fact, a forest fire plume greatly enriched in NH_4^+, $C_2O_4^{2-}$ and K^+ originating in the Hudson Bay lowlands has been sampled in real-time at Summit, Greenland (Dibb *et al.*, 1996). Greenland ice cores show increased forest fire activity in North America between 1790 and 1810 and again from 1830 to 1910 (Whitlow *et al.*, 1994). The latter period reflects the large-scale burning of forests to clear land for agricultural use during the westward expansion of North American settlement referred to as the Pioneer Agricultural Revolution (Holdsworth *et al.*, 1996). The post-1910 decrease in forest fire activity reflects the increasing importance of active fire suppression in eastern North America (Whitlow *et al.*, 1994). An earlier period of enhanced forest fire activity between AD 1200 and 1350 possibly reflects warmer and drier climatic conditions during the 'Mediaeval Warm Period' (Savarino and Legrand, 1998). The Mt Logan ice core records forest fires in northwest North America and Siberia, with periods of high fire activity from 1770 to 1790, 1810 to 1830, 1850 to 1870 and 1930 to 1980 (Whitlow *et al.*, 1994). In fact, plumes from forest fires burning in Alaska and the Yukon have been directly observed over the Mt Logan region (Holdsworth *et al.*, 1996). Prior to the building of the Trans-Siberia railroad, lightning probably caused most fires in Siberia because of a relative lack of anthropogenic ignition sources (Stocks, 1991); hence ice cores from Mt Logan may document a forest fire–climate relationship relatively free of anthropogenic influences (Whitlow *et al.*, 1994).

Here we develop a record of forest fire activity spanning the last 100 to 1000 years using three ice cores from Eclipse Icefield (60.51°N, 139.47°W, 3017 m elevation), St Elias Mountains, Yukon, Canada (Figure 1). Although only 45 km northeast of the high elevation ice core sites on Mt Logan, the Eclipse Icefield provides a distinct record because of the difference in elevation between the two sites, which allows the sites to sample different layers of the atmosphere (Yalcin and Wake, 2001; Wake *et al.*, 2002; Yalcin *et al.*, 2003). The availability of three ice cores from Eclipse Icefield allows us to investigate the variability in forest fire signal preservation and improve confidence in our reconstructions of forest fire activity.

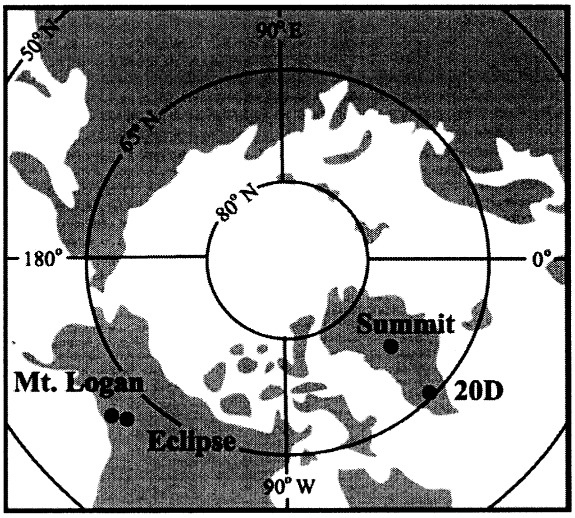

Figure 1 Location of Eclipse Icefield and other ice core sites discussed in this paper

Ice core analysis and dating

A 160 m ice core was recovered from Eclipse Icefield in 1996 (Yalcin and Wake, 2001). Two additional cores (345 m and 130 m) drilled 1 m apart were recovered in 2002, 100 m up the flow line from the 1996 drill site. All three cores were sampled continuously at high resolution for major ions and stable isotopes to establish a detailed chronology for the core. Sample resolution ranged from 6 to 15 cm for major ions and 2 to 15 cm for stable isotopes. Stringent core processing techniques were used to ensure samples were contamination-free at the ng/g level. Blanks prepared on a frequent basis showed no contamination of samples during processing of the core. Samples were analysed for major ions (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}, $C_2O_4^{2-}$) via ion chromatography using a 0.5 ml sample loop in a dedicated laboratory at the University of New Hampshire Climate Change Research Center. The cation system used a CS12A column with CSRS-ultra suppressor in auto suppression recycle mode with 20 mM MSA eluent. The anion system used an AS11 column with an ASRS-ultra suppressor in auto suppression recycle mode with 6 mM NaOH eluent. Oxalate was not quantified in the 1996 core. Stable isotope samples were analysed at the University of Maine Stable Isotope Laboratory with a Multiprep CO_2 equilibration system coupled to a VG SIRA mass spectrometer for $\delta^{18}O$ (precision ± 0.05‰) and a Eurovector Cr pyrolosis unit coupled to a GV Isoprime mass spectrometer for δD (precision ± 0.5‰). A section of each core was analysed for radionuclides (^{137}Cs) via gamma spectroscopy.

All three cores show similar radionuclide profiles, with clear identification of the 1963 and 1961 peaks from atmospheric thermonuclear weapons testing that were observed in real-time aerosol samples collected at Whitehorse, Yukon by the Radiation Protection Bureau, Ottawa (Figure 2). Radioactive fallout from the 1986 Chernobyl nuclear power plant accident was also detected, providing an additional stratigraphic marker. Average annual accumulation from 1963 to 2002 was 1.30 m water equivalent. The presence of discrete ice layers in the Eclipse ice core averaging 5% of the net accumulation by weight demonstrates that a limited amount of surface melting occurs at the Eclipse site during summer. Meltwater percolation does not significantly alter the glaciochemical records available from the Eclipse ice core as evidenced by the preservation of clear seasonal signals in the major ion and oxygen isotope records, allowing dating of the cores via multiparameter annual layer counting (Figure 2).

Annual layers were identified by summer–winter variations in oxygen isotope ratios and sodium concentrations. The annual cycle of $\delta^{18}O$ maxima in summer precipitation and $\delta^{18}O$ minima in winter precipitation observed at Eclipse is related at least in part to the temperatures at which evaporation at the source and cloud condensation of the precipitation occurs (Dansgaard *et al.*, 1973). The annual cycle of Na^+ concentration maxima in winter and minima in summer is related to pronounced seasonal changes in the influx of marine aerosols (Whitlow *et al.*, 1992). Increased storminess and higher wind speeds in the Gulf of Alaska during winter results in enhanced entrainment of sea salt aerosols and more frequent advection of marine air masses into the St Elias Mountains, producing the observed winter peaks in sodium concentrations. Age control on the chronology established via annual layer counting is provided by the 1986, 1963 and 1961 ^{137}Cs reference horizons as well as volcanic reference horizons (eg, Katmai 1912; Tambora 1815; Laki 1783, Kuwae 1453) developed through statistical analysis of the high-resolution sulfate record (Yalcin *et al.*, 2003). In some cases, these identifications have been independently verified using tephrochronology by comparing the major oxide composition of volcanic glass shards found in the ice core to tephra samples from suspected source volcanoes (Figure 2).

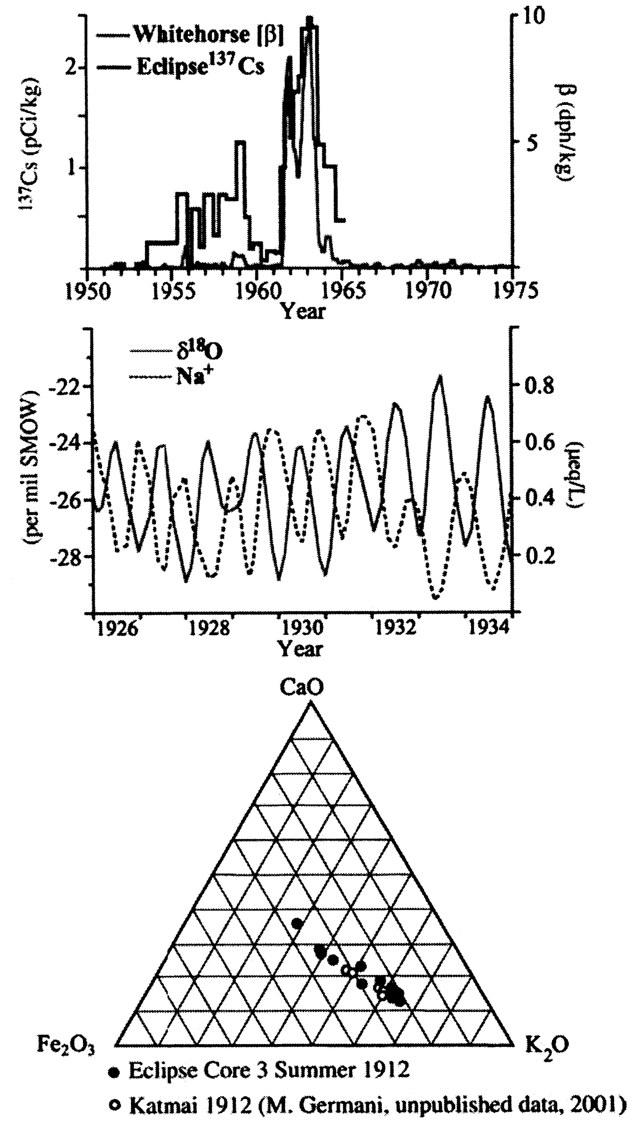

Figure 2 Parameters used in dating of the Eclipse ice cores. Top: comparison of Eclipse ice core ^{137}Cs profiles with real-time aerosol samples from Whitehorse, Yukon Territory shows clear identification of the 1963 and 1961 radionuclide peaks from atmospheric nuclear weapons testing. Middle: seasonal signals in the smoothed $\delta^{18}O$ and Na^+ records used to date the Eclipse ice cores via annual layer counting. Bottom: major oxide composition of volcanic glass shards found in the summer 1912 layer of all three Eclipse ice cores closely matches the composition of volcanic glass produced by the June 1912 eruption of Katmai, Alaska; providing tephrochronological reference horizons to verify the chronology developed by annual layer counting

Identification of forest fire signals

We used two techniques to identify forest fire signals in our records. First, a robust spline was used to estimate the time-varying background NH_4^+ concentrations that represent ammonia emissions from soils and plants (Taylor *et al.*, 1996; Meeker *et al.*, 1997). Residuals above the spline greater than one standard deviation above the mean positive residual (0.6 μeq/L) are then taken to represent forest fire signals (Figure 3). Although NH_4^+ in polar snow and ice has other sources

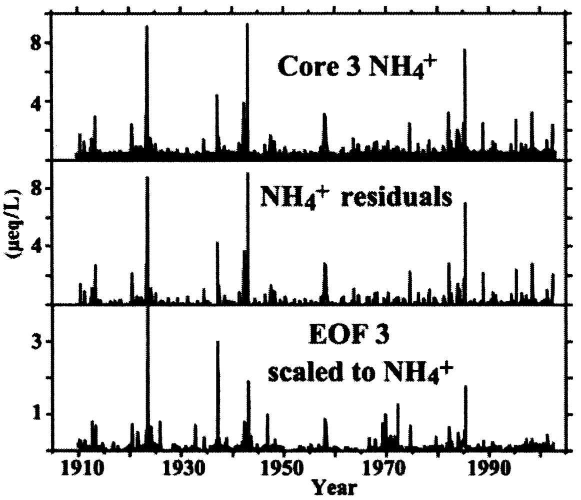

Figure 3 Identification of forest fire signals in the Eclipse 2002 Core 3 ice core. Top: The NH_4^+ time series is smoothed with a robust spline to estimate background NH_4^+ concentrations (denoted by solid grey area). Middle: the residuals above the spline are considered to represent forest fire signals. Bottom: the EOF 3 time series, scaled to NH_4^+. Note the different scale of the Y-axis used to plot the EOF 3 time series

including emissions from vegetation and soil microbial activity (Meeker *et al.*, 1997), large, short-term increases in ammonium such as those we have identified as residuals above a robust spline are uniquely associated with forest fires (Taylor *et al.*, 1996). Furthermore, the concentration increases, which we have identified as NH_4^+ residuals, are not due to changes in accumulation rate because there is no significant correlation between NH_4^+ concentration and snow accumulation (Yalcin *et al.*, 2006).

We also used an empirical orthogonal function (EOF) analysis to identify forest fire signals. The EOF analysis splits the temporal variance of a multivariant data set into patterns termed empirical eigenvectors that are orthogonal in nature (Peixoto and Oort, 1992). The first eigenvector explains the greatest percentage of variance in the data set, with each successive eigenvector describing the maximum remaining variance. Since the modes are orthogonal, there is no correlation between any two modes. This allows differentiation of sources and transport characteristics by relationships between individual species as described by each EOF (Mayewski *et al.*, 1994). Therefore, each EOF can provide information on a different environmental parameter controlling the glaciochemistry of an ice core.

Applying EOF analysis to the suite of ions measured in the Eclipse 2002 ice cores reveals that NH_4^+, K^+ and $C_2O_4^{2-}$ are loaded on EOF 3 which describes 14% of the variance in the full data set and 25% to 28% of the variance in these three species produced by forest fires (Table 1). The Eclipse 1996 ice core is also loaded with NH_4^+ and K^+ on EOF 3, suggesting similar behavior despite the lack of $C_2O_4^{2-}$ analyses for this core. Comparison of the EOF 3 time series with the raw NH_4^+, K^+ and $C_2O_4^{2-}$ time series shows that EOF 3 picks up nearly all the NH_4^+ and $C_2O_4^{2-}$ peaks, as well as those K^+ peaks associated with peaks in NH_4^+ and $C_2O_4^{2-}$. Furthermore, inspection of the EOF 3 time series reveals an episodic character in the species of interest (Figure 3), as would be expected if EOF 3 represents an episodic forcing such as forest fire events. The similarity between the chemical association identified by EOF 3 and the chemical enhancements observed in forest fire plumes as well as the similarity to the NH_4^+ residual time series leads us to conclude that EOF 3 provides a record of forest fire activity.

These two approaches for identifying forest fire signals provide similar records of fire activity (Figure 3). However, there are some events identified as NH_4^+ residuals that are not identified by the EOF analysis since they are not associated with concurrent enhancements of K^+ and $C_2O_4^{2-}$. Furthermore, NH_4^+ concentrations provided by EOF 3 (mean plus one standard deviation equal to 0.3 µeq/L) are about one-half those given by the NH_4^+ residuals (mean plus one standard deviation equal to 0.6 µeq/L). For these reasons we feel that the EOF analysis provides a more conservative identification of forest fire signals, since it identifies only those events with enhancements in all three species. Since $C_2O_4^{2-}$ was not quantified in the Eclipse 1996 ice core, the EOF 3 time series are not directly comparable between the 1996 and 2002 cores. We therefore limit the remainder of our discussion to events identified as NH_4^+ residuals in order to incorporate data from all three cores in our analysis. Since most events (70%) are identified as both NH_4^+ residuals and by EOF analysis, either technique yields a similar proxy for forest fire activity. The chemical association described by EOF 3 provides an additional line of evidence supporting the interpretation of NH_4^+ peaks in our record as forest fire signals because EOF 3 provides a multiparameter record of enhancements in NH_4^+, K^+ and $C_2O_4^{2-}$, all species that are produced by forest fires. Studies of forest fire records from Greenland ice cores report that concurrent

Table 1 Eclipse 2002 core 3 EOF analysis

	Normalized eigenmodes[a]				Percent variance explained[b]			
	EOF 1	EOF 2	EOF 3	EOF 4	EOF 1	EOF 2	EOF 3	EOF 4
Na^+	0.44	0.78	0.24	−0.18	19.3	60.3	5.5	3.3
NH_4^+	0.54	−0.49	0.50	−0.14	29.1	24.3	24.8	1.9
K^+	0.44	0.25	0.49	0.68	19.3	6.1	24.5	46.3
Mg^{2+}	0.73	0.05	−0.46	0.23	52.7	0.2	21.4	5.3
Ca^{2+}	0.86	−0.11	−0.37	0.13	74.0	1.1	13.7	1.7
Cl^-	0.55	0.72	0.14	−0.27	29.8	51.3	1.9	7.3
NO_3^-	0.78	−0.33	−0.14	−0.09	60.3	11.0	2.0	0.8
SO_4^{2-}	0.83	−0.05	−0.20	−0.17	68.8	0.3	4.1	2.8
$C_2O_4^{2-}$	0.50	−0.44	0.53	−0.15	25.2	19.1	28.0	2.1
Total					42.0	19.3	14.0	8.0

[a] Correlation coefficient (*r*-value) between EOF time series and glaciochemical time series.
[b] *R*-squared value between EOF time series and glaciochemical time series.

enhancements in other species such as K^+ or organic acids are needed to confidently attribute ice core NH_4^+ spikes to forest fires (Whitlow *et al.*, 1994; Savarino and Legrand, 1998). Since most of the NH_4^+ spikes in the Eclipse ice cores are also identified by the multiparameter EOF analysis, forest fires may be the only significant source of NH_4^+ spikes in our cores. Greenland may be affected by other NH_4^+ sources necessitating corroboration of suspected forest fire signals using other glaciochemical records such as organic acids.

Validation of the record

To validate our record as a proxy for forest fire activity, we compared our results with records of annual area burned in potential forest fire source regions affecting Eclipse Icefield. It is important to note that fire activity and annual area burned are not synonymous, since a small percentage (3%) of fires account for the vast majority (98%) of acreage burned each year (Stocks *et al.*, 2002). However, periods of increased fire activity can be expected to correspond with larger areas burned. We considered two potential forest fire source regions: Alaska, for which annual area burned statistics are available since 1940 from the Alaska Fire Service, Bureau of Land Management, Fairbanks, Alaska, as discussed in detail by Kasischke *et al.* (2002); and the Yukon, for which annual area burned statistics are available since 1946 (Weber and Stocks, 1998). Since the lifetime of tropospheric NH_4^+ aerosol is on the order of 1–2 weeks, NH_4^+ from forest fires in these regions can be transported sufficient distances to reach Eclipse. A third possible source area, British Columbia, does not appear to be an important source region for forest fires affecting Eclipse Icefield, since most forest fires in the province are well downwind of Eclipse to the south and east (Taylor and Thandi, 2002).

We evaluated the preservation of forest fire signals as NH_4^+ residuals at Eclipse during years of high fire activity in Alaska and the Yukon (Table 2). High fire years are defined as years in which the area burned was more than 1.5 times the long-term average (Kasischke *et al.*, 2002). For Alaska, a high fire year is one with more than 530 000 ha burned, while a high fire year in the Yukon burns more than 168 000 ha because of the smaller area covered by boreal forest in the Yukon relative to Alaska. Although only one in four years can be considered a high fire year based on annual area burned statistics, high fires years account for the majority (60%) of the total area burned in historical records (Kasischke *et al.*, 2002). Therefore, high fire years are those of the most importance in reconstructing past forest fire activity. Our analysis indicates that 80% and 79% of high fire years in Alaska and the Yukon, respectively, are recorded as NH_4^+ residuals in at least one of the Eclipse ice cores (Table 2). Furthermore, we found nearly equal sensitivity of our record to high fire years in Alaska and the Yukon, suggesting that Alaska and the Yukon are probably equally important source regions for forest fires impacting Eclipse Icefield. Interestingly, only three years (1950, 1969 and 1977) qualify as high fire years in both Alaska and the Yukon, suggesting considerable regional variability in fire activity.

Given year-to-year variations in meteorological conditions and the remoteness of the Eclipse site at 3017 m elevation from forested regions, it is not surprising that some high fire years in Alaska and the Yukon are not recorded at Eclipse. Nonetheless, this comparison provides evidence that our record provides a

Table 2 High fire years recorded in the Eclipse ice cores[a]

High fire years in Alaska[b]					High fire years in Yukon[c]				
Year	Hectares	Core 1	Core 2	Core 3	Year	Hectares	Core 1	Core 2	Core 3
2002	883 576	–	Y	Y	1999	194 456	–	Y	
1997	774 696	–		Y	1998	343 672	–	Y	Y
1991	708 766	Y		Y	1995	261 380	Y	Y	Y
1990	1 291 125	Y		Y	1994	421 710	Y		Y
1988	885 841	Y	Y	Y	1989	383 188			Y
1977	960 342	Y			1982	240 111	Y	Y	Y
1969	1 713 287	Y			1977	312 469	Y		
1961	553 318				1971	301 730	Y		
1957	2 044 397	Y		Y	1969	618 109	Y		
1954	562 721				1966	191 648	Y	Y	
1950	1 221 016		Y		1958	889 032		Y	Y
1947	578 905	Y	Y	Y	1953	175 800			
1946	581 618	Y	Y	Y	1951	339 151	Y		
1941	1 476 022		Y	Y	1950	177 024			
1940	1 821 862								

Summary

Percent high fire years recorded (Alaska)					Percent high fire years recorded (Yukon)				
At least one core	More than one core	Core 1	Core 2	Core 3	At least one core	More than one core	Core 1	Core 2	Core 3
80% (12/15)[d]	47% (7/15)	62% (8/13)	40% (6/15)	60% (9/15)	79% (11/14)	36% (5/14)	67% (8/12)	36% (5/14)	43% (6/14)

[a] Y denotes NH_4^+ residuals detected in ice core during that year and – denotes a high fire year that is outside the period of record for that core (Core 1 1894–1996; Core 2 1000–2002; Core 3 1910–2002).

[b] Alaska annual area burned data from the Alaska Fire Service, Bureau of Land Management, Fairbanks, as discussed by Kasischke *et al.* (2002).

[c] Yukon annual area burned data from Government of Yukon Department of Community Services: http://www.community.gov.yk.ca/firemanagement/sts46.html.

[d] Number of high fire years recorded out of total possible for that core or group of cores.

reasonable proxy for forest fire activity in these regions, with about four out of every five high fire years identifiable in the record. However, NH_4^+ concentration spikes frequently occur in years with less than 200 000 ha burned, suggesting our record is sensitive to less intense fire activity in nearby areas (southwest Yukon or east-central Alaska) or to meteorological conditions favourable for transport and preservation of forest fire plumes at Eclipse Icefield. It is important to reiterate that quantitative information on the size of a given fire year can not be extracted from ice core data because of year-to-year differences in atmospheric circulation pathways and transport distances between burned areas and an ice core site. For these reasons there is no predictable relationship between size of a fire year and peak NH_4^+ concentrations in glacial ice.

Reconstruction of fire activity

Fire activity over the last 250 years

We use the proxy for forest fire activity provided by NH_4^+ residuals in the Eclipse ice cores to reconstruct fire activity in the Yukon region over two time periods: the last 250 and last 1000 years. All ice core data were resampled at a constant resolution of eight samples per year for the last 250 years to avoid spurious trends resulting from changing sample resolution. To identify intervals of high and low fire activity in our record, we counted the number of samples per decade whose NH_4^+ residual value exceeds the signal threshold of one standard deviation above the mean positive residual (Figure 4). For time intervals where more than one core is available from Eclipse Icefield, the average number of events recorded is represented by the bar with the number of events recorded in each individual core presented as solid black circles. The average number of fire events recorded per decade at Eclipse Icefield between 1750 and 2000 is six.

The Eclipse ice cores indicate high forest fire activity in the 1760s, 1780s, 1840s, 1860s, 1880s, 1890s, 1920s–1940s and 1980s. Our record suggests the highest forest fire activity during the last 250 years in this region occurred during the 1890s, coinciding with the discovery of gold in the Yukon and the Klondike Gold Rush. This may represent an anthropogenic influence on fire activity associated with the first large influx of miners and settlers into the Yukon. Our record indicates low fire activity in the 1770s, 1810s–1830s, 1850s, 1950s and 1960s. Records of forest fire activity provided by the three Eclipse ice cores are in agreement 70% of the time, with exceptions arising from a higher number of events recorded in one of the three cores during the decades of the 1930s, 1970s and 1980s. The observed spatial variability in the preservation of glaciochemical signals from forest fires could be a result of reworking of the snow surface by blowing and drifting snow, resulting in an uneven layer thickness for distinct chemical horizons (Dibb and Jaffrezo, 1997). Nonetheless, the fact that three ice cores from Eclipse Icefield indicate similar levels of fire activity 70% of the time provides confidence in our reconstruction of forest fire activity.

Similar NH_4^+ concentrations between the Eclipse, Mt Logan (Yukon) and 20D (Greenland) ice cores permits direct comparison of our record of forest fire activity developed from the Eclipse ice cores with the records from the Mt Logan and 20D ice cores presented by Whitlow *et al.* (1994). For consistency, we also resampled the original Mt Logan and 20D NH_4^+ time series at constant resolution of eight samples per year. As for Eclipse, we used a robust spline to estimate background NH_4^+ concentrations and counted the number of samples per decade whose NH_4^+ residual consideration above the spline exceeds the signal threshold of one standard deviation above the mean positive residual. Somewhat surprisingly, comparison of the records demonstrates closer agreement between the Eclipse and 20D records than between the Eclipse and Mt Logan records (Figure 4). For example, Eclipse and 20D indicate low fire activity during the 1950s and 1960s, while Mt Logan suggests the 1950s and 1960s were a period of high fire activity. Conversely, Eclipse and 20D indicate high fire activity in the 1880s, 1890s, 1920s and 1940s, while Mt Logan suggests low or moderate fire activity. The correlation coefficient for decadal fire activity between Eclipse and 20D is 0.28 while it is only 0.08 between Eclipse and Mt Logan, although these correlations are not statistically significant. A notable exception occurs during the 1830s and 1850s, when both the Eclipse and Logan records indicate low fire activity, while the 20D record indicates high fire activity. This breakdown in the correspondence of high fire activity in eastern and northwest North America could be a result of the expansion of settlement and agriculture and associated biomass burning in eastern and central North America in the early to mid 1800s, a source region for forest fire plumes affecting Greenland. Meanwhile, northwest North America remained relatively free of anthropogenic ignition sources during this time.

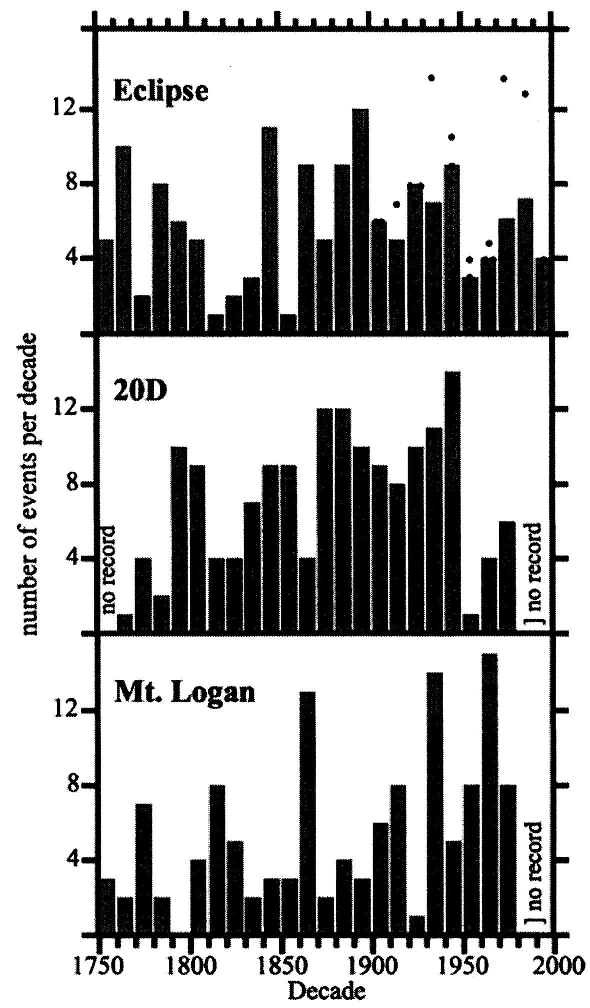

Figure 4 Reconstruction of forest fire activity since 1750 using the Eclipse ice cores (top). Post 1900, the bar represents the average number of forest fire events recorded per decade in the multiple ice cores available, with the number of events recorded in each individual core indicated by solid black circles. From 1910 to 1990 three cores from Eclipse are available, with two cores available from 1900 to 1910 and 1990 to 2000. The Eclipse forest fire record is compared with other ice core proxies of forest fire activity from 20D, South Greenland (middle) and Mt Logan, Yukon (bottom)

Fire activity over the last 1000 years

Prior to 1750, layer thinning limits the temporal resolution available from the Eclipse ice core NH_4^+ record. However, annual concentration data can be used to extend the Eclipse record to AD 1000. Although annual data lack the temporal resolution to reconstruct fire activity in the same terms used for the period 1750–2000, we can nonetheless analyse the record for fire signals in the same way using a robust spline and consider the residuals above the spline. Our results suggest high forest fire activity during the period 1240 to 1410 (Figure 5) possibly reflecting climatic conditions during the waning stages of the 'Mediaeval Warm Period'. The 'Mediaeval Warm Period' has been variously dated to AD 900–1200 (Jones *et al.*, 2001) or AD 1000–1300. (Crowley and Lowery, 2000) but is sometimes used to refer to any climatic anomaly between AD 500 and 1500 (Bradley *et al.*, 2003). Furthermore, the 'Mediaeval Warm Period' was not globally synchronous nor was it continuously warm (Hughes and Diaz, 1994; Mann *et al.*, 1999).

The period of high fire activity in the Eclipse ice core between 1240 and 1410 should correspond to warmer and drier conditions in Alaska and the Yukon, as has been demonstrated for years of high fire activity during the twentieth century (Flannigan and Harrington, 1988; Kasischke *et al.*, 2002). Corroborating evidence for climatic conditions favourable to forest fire activity during the waning stages of the 'Mediaeval Warm Period' is available from regional palaeoclimatic reconstructions including glacier fluctuations, tree rings and lake sediment cores. Although there is a time lag between climatic change and glacier response, the records of alpine glacier fluctuations considered here are sensitive to decadal- to centennial-scale climate variations (Wiles *et al.*, 1999). The earliest glacier advances in the Wrangell and St Elias Mountains and in coastal Alaska during the past millennium, as documented by kill dates of trees overrun by ice, were centred around AD 1250 (Wiles *et al.*, 1999, 2002; Calkin *et al.*, 2001). This was followed by a period of general glacier retreat in Alaska and the Yukon in response to warmer and/or drier conditions that prevailed between about 1300 and 1450 (Wiles *et al.*, 2004) but ending by the early 1400s in coastal portions of Alaska (Calkin *et al.*, 2001). Likewise, tree-ring-width indices from western Prince William Sound, Alaska, suggest a multidecadal warm period centred on AD 1300 (Barclay *et al.*, 1999), while tree-ring-based reconstructions of summer temperatures in the Canadian Rockies show a warm period *c.* 1350–1440 (Luckman *et al.*, 1997). A lake-sediment record from the Alaska Range suggests a more prolonged period of relative warmth from AD 850 to 1450 (Hu *et al.*, 2001).

The inferred climatic conditions in Alaska and the Yukon favouring glacier retreat and high forest fire activity during the waning stages of the 'Mediaeval Warm Period' may have been forced by increased solar irradiance in conjunction with a sustained warm phase of the Pacific Decadal Oscillation (Wiles *et al.*, 2004). This interval was followed by renewed 'Little Ice Age' glacial advances throughout Alaska reflecting cooler and/or wetter conditions that culminated between 1650 and 1850 (Wiles *et al.*, 1999, 2002; Calkin *et al.*, 2001). 'Little Ice Age' cooling is also evident in lake sediments from the Alaska Range between 1450 and 1850 (Hu *et al.*, 2001). Tree-ring-width chronologies from coastal Alaska do not indicate a level of warmth comparable with the early 1300s until after 1800 (Barclay *et al.*, 1999). The cooler and/or wetter conditions prevailing during the 'Little Ice Age' are reflected in the Eclipse ice core by a decrease in forest fire activity after 1410.

Higher frequency of ammonium and formate concentration spikes in the Summit, Greenland EUROCORE suggests a similar increase in fire activity between 1200 and 1350 coincident with the warm and dry conditions of the 'Mediaeval Warm Period' (Savarino and Legrand, 1998). There is also evidence of elevated rates of charcoal accumulation in lake sediment cores from interior Alaska during this same time period (Lynch *et al.*, 2003). Elsewhere, frequent peaks in charcoal abundance are noted in lake sediment records from southeastern British Columbia between 980 and 1300 (Hallett *et al.*, 2003) and Finland between 1380 and 1470 (Pitkanen and Huttunen, 1999); while higher fire frequency is suggested by fire-scarred tree-rings in giant sequoias of the Sierra Nevada, California, between 1000 and 1300 (Swetnam, 1993). Meanwhile, the ECM record of the GISP2 ice core suggests a more prolonged and somewhat later period of high fire activity from AD 1250 to 1650 (Taylor *et al.*, 1996).

Differences in the regional timing of high fire activity associated with the 'Mediaeval Warm Period' are not unexpected considering that the 'Mediaeval Warm Period' was neither globally synchronous nor continuously warm (Hughes and Diaz, 1994; Mann *et al.*, 1999). When viewed in climatic context, the Eclipse record and other fire activity proxies indicate the warm and dry conditions of the 'Mediaeval Warm Period' were more favourable for forest fire activity in the boreal region than at any other time during the last 1000 years. However, in some areas such as the Kenai Peninsula of Alaska, anthropogenic influences over the last 150 years have resulted in even higher fire activity than during the 'Mediaeval Warm

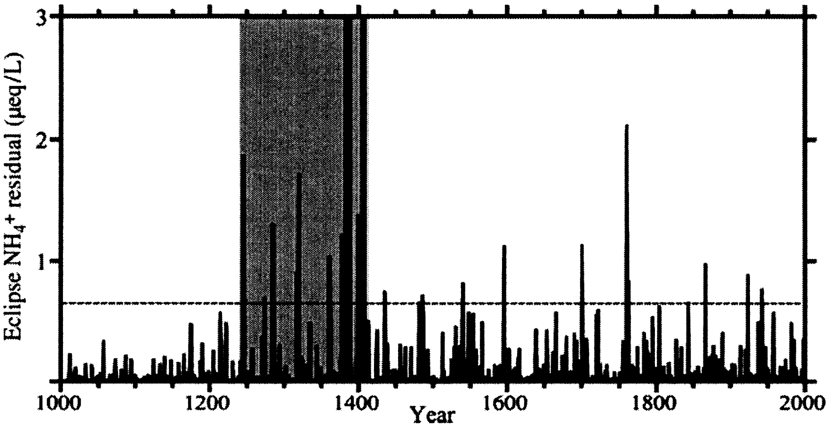

Figure 5 Evaluation of forest fire signals using annual NH_4^+ residuals from Eclipse Icefield suggest the period 1240–1410 (shaded) was the most prolonged period of high fire activity in the Yukon and Alaska in the last 1000 years. Dashed line indicates one standard deviation above the mean positive NH_4^+ residual

Period' climatic optimum (Lynch *et al.*, 2003). This is not observed in the Eclipse record, which records forest fires in more remote boreal regions of Alaska and the Yukon, although anthropogenic influences on forest fire activity are suggested by high forest fire activity coincident with the Klondike Gold Rush of the 1890s. Nonetheless, the sensitivity of fire regimes to climatic change is illustrated by these records. If the 'Mediaeval Warm Period' provides a suitable analogy for climatic conditions in the era of anthropogenic greenhouse gas warming, the palaeoenvironmental record seems to confirm predictions of increased fire activity in the boreal region during the twenty-first century.

Conclusions

We have presented a proxy of forest fire activity using ice cores from Eclipse Icefield, Yukon, Canada. Forest fire signals were identified by NH_4^+ residuals above a robust spline and by an EOF analysis that identified a chemical association in the NH_4^+, $C_2O_4^{2-}$ and K^+ records similar to that seen in forest fire plumes. Since 70% of the events are identified by both NH_4^+ residuals and in the EOF analysis, a similar record is obtained using either technique. Comparing our fire activity proxy to records of annual area burned in Alaska and the Yukon since 1940 and 1946, respectively, demonstrates the Eclipse ice cores provide a good proxy for fire activity in these regions since four out of every five high fire years in Alaska and the Yukon are identifiable as NH_4^+ residuals at Eclipse Icefield. Furthermore, the three cores from Eclipse agree well with respect to decadal fire activity 70% of the time, allowing us to reconstruct fire activity since 1750 with reasonable confidence. The Eclipse ice cores record high fire activity in the 1760s, 1780s, 1840s, 1860s, 1880s, 1890s, 1920s–1940s and 1980s. Peak fire activity occurred in the 1890s, possibly reflecting anthropogenic ignition sources associated with the first large-scale influx of settlers and miners into the Yukon during the Klondike Gold Rush. Periods of low fire activity are evident during the 1770s, 1810s–1830s, 1850s, 1950s and 1960s. Extending our proxy of fire activity to AD 1000 using annual NH_4^+ concentrations from a single core provides evidence of high fire activity during the waning stages of the 'Mediaeval Warm Period' from 1240 to about 1410. If the 'Mediaeval Warm Period' does provide a suitable analogy for future climatic conditions resulting from anthropogenic greenhouse gas emissions, then high fire activity in Alaska and the Yukon seems likely during the twenty-first century.

Our results are compared and contrasted with other ice core proxies of forest fire activity from 20D and Summit, Greenland and Mt Logan, Yukon. Somewhat surprisingly, the Eclipse record correlates best with the records from Greenland, with periods of high and low fire activity synchronous in eastern and northwestern North America. This correlation between Eclipse and Greenland breaks down during periods of pioneer land clearing for agriculture in eastern North America that are well recorded in Greenland but for which no evidence is seen in the Eclipse ice core since it is located upwind of the regions affected. Furthermore, both the Eclipse and Summit, Greenland ice cores provide evidence of high fire activity during the later part of the 'Mediaeval Warm Period' between about AD 1200 and 1400. Ice core proxy records of boreal forest fire activity such as the one presented here are useful for evaluating the response of boreal forest fire regimes to climate change, potentially corroborating model projections of increased fire activity in response to projected climate change in the twenty-first century.

The apparent uniqueness of the Mt Logan forest fire source region suggests that the Mt Logan summit plateau records primarily Siberian forest fires, suggesting that the new ice cores from Mt Logan (Fisher *et al.*, 2006) and Belukha Glacier in the Siberian Altai (Olivier *et al.*, 2003) may be suitable for reconstruction of Siberian forest fire activity. Although government-compiled fire statistics are available for Russia (Korovin, 1996), comparison of official fire statistics to burned area estimates derived from satellite data (Sukhinin *et al.*, 2004) shows no correlation between the two, indicating the official fire statistics do not provide an unbiased sample of fire activity in Siberia. The Mt Logan and Belukha Glacier ice cores could be used to develop a record of forest fire activity in Siberia where reliable documentary evidence of fire activity is essentially non-existent prior to the advent of remote sensing technologies (Sukhinin *et al.*, 2004).

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