

Record-breaking 2023 fires signal a new era of smoke-driven darkening on the Greenland Ice Sheet

Alia Khan

alia.khan@colorado.edu

University of Colorado - Boulder <https://orcid.org/0000-0002-4425-1528>

Ella Hall

Western Washington University <https://orcid.org/0009-0003-0374-9068>

Peng Xian

Aerosol and Radiation Section of the Marine Meteorology Division, Naval Research Laboratory

Article

Keywords:

Posted Date: May 11th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9571979/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations:

There is **NO** Competing Interest.

Figure 6 is not available with this version

Record-breaking 2023 fires signal a new era of smoke-driven darkening on the Greenland Ice Sheet

Abstract

Boreal wildfires, intensified by warming, transport smoke aerosols to the Greenland Ice Sheet (GrIS), reducing surface albedo and accelerating melt. Using two decades (2003–2023) of aerosol model fluxes and surface observations, we identify a structural shift toward intensified smoke loading since 2019. This peaked during the record-breaking 2023 Canadian wildfire season, which contributed >20% of total deposition since 2003, with southern GrIS anomalies reaching ten times the 20-year average. Persistent "heat domes" and pyrocumulonimbus events likely facilitated this exceptionally efficient transport. We demonstrate that in 2023, smoke deposition was the primary driver of albedo variability in the ablation zone, explaining 46.4% of the variance—nearly five times the influence of air temperature. These results indicate that the record-breaking 2023 season serves as a harbinger of a new regime where smoke-driven surface darkening plays a critical role in Arctic melt-albedo feedbacks, potentially decoupling ice-sheet mass loss from traditional thermodynamic drivers.

Introduction

An increase in the frequency, duration, and intensity of Northern Hemisphere boreal wildfires in recent decades, driven by anthropogenic climate change, has resulted in greater emissions of smoke aerosols available for long-range atmospheric transport^{1–5}. Wildfire smoke is the primary source of BC in the Arctic⁶, and while local fires can contribute to atmospheric aerosol loading (e.g.⁷, most of the smoke that reaches the Arctic is carried northward from source regions in North America and Siberia by strong westerly winds and large-scale circulation patterns that enable long-range transport^{8–10}. Wildfire smoke contains black carbon (BC), the strongly light-absorbing component of soot, and the second most important climate forcer after CO₂, due to its ability to absorb solar radiation both in the atmosphere and when deposited on snow and ice by darkening the surface^{11,12}. Even small concentrations of BC deposited on snow - on the order of tens of nanograms per gram - can significantly enhance solar absorption, leading to accelerated melt^{12–14}.

The deposition of BC initiates a melt-albedo feedback whereby the surface is darkened, melt is enhanced, underlying grain structures coarsen and impurities become more concentrated at the surface, further lowering albedo and amplifying melt rates¹⁵. Increasing wildfire smoke deposition on the Greenland Ice Sheet (GrIS)¹⁶ is of particular concern because the GrIS is highly susceptible to darkening by light-absorbing particles (LAPs) like BC, that can increase surface melt, which is the primary driver of ice sheet mass loss^{17–19}. The southwestern region of the GrIS has been melting the fastest²⁰, which is suspected to be driven by the accumulation and exposure of dark LAPs like BC^{20–23}. The GrIS is likely to experience increasing surface melt, with the potential to contribute 7 meters to global sea-level rise²⁴, making it critical to understand how

changing wildfire smoke deposition patterns may further enhance albedo-driven melt under a warming climate.

Boreal forests have been disproportionately impacted by climate change, due to Arctic Amplification: a phenomenon that is causing the Arctic to warm 2-3 times faster than the rest of the planet²⁵. These regions have experienced especially pronounced increases in extreme fire weather^{26,27}, with Canada's climate in particular, warming faster than the global average rate with the average annual temperature increasing by 1.7 °C since 1948²⁸. The shift toward more extreme wildfire seasons was evident during the summer of 2023, when Canada experienced the most extreme wildfire season in its history with over 15 million hectares burned between April and October - seven times higher than the annual average area burned, and two times higher than the previous record^{29,30}. The 2023 Canadian wildfires produced the highest carbon emissions on record, emitting around 480 million tonnes of Carbon - over five times the average annual carbon emissions from wildfires during the previous 20 years³¹. Extreme heat, early snowmelt, and prolonged drought contributed to widespread ignition and rapid fire spread, enabling fires to grow larger and last longer²⁹. As climate change progresses, extreme wildfire seasons like the 2023 Canadian season are projected to become more common¹⁻⁵.

Smoke transport to the GrIS from northern hemisphere wildfires has been well documented. Previous studies have investigated wildfire smoke deposition on the GrIS using snow pit analyses and surface samples^{7,21,32,33}, however, these measurements have been spatially and temporally limited, leaving the broader patterns of smoke deposition across the GrIS largely unresolved. To date, there have not been any studies that have assessed spatiotemporal trends in smoke deposition on the GrIS on a multi-decadal, ice-sheet wide scale. Variability in smoke deposition, driven by shifts in atmospheric circulation and the seasonality of wildfire activity, further complicates efforts to understand how smoke influences ice-sheet energy balance and melt processes when relying on localized in-situ campaigns^{1,33}. Additionally, there have not been any studies that have compared the impacts of wildfire smoke deposition from the record-breaking 2023 Canadian wildfire season on the GrIS.

Here, we address these gaps by using modeled smoke deposition fluxes from the Navy Aerosol Analysis and Prediction System (NAAPS) reanalysis model across ten transects of the GrIS to characterize spatial and temporal patterns of wildfire smoke deposition from 2003 – 2023, and to compare smoke deposition in 2023 to the previous 20-year average. We further evaluate the relative impacts of wildfire smoke compared to other albedo-reducing variables by integrating observations from Programme for the Monitoring of the Greenland Ice Sheet (PROMICE) and Greenland Climate Network (GC-Net) automatic weather stations into generalized additive models (GAMs), allowing us to assess smoke-driven albedo variability in different regions of the GrIS, and under extreme smoke loading during 2023. With this, we provide a novel analysis of wildfire smoke deposition on the GrIS, showing how deposition patterns have shifted under a warming climate and how extreme smoke events may affect the ice sheet under projected climate scenarios.

Results

Long-Term Smoke Deposition Trends

While annual smoke deposition across the Greenland Ice Sheet (GrIS) exhibited no significant linear trend over the 2003–2023 period (Fig. 1a), these multi-decadal averages obscure a critical recent transition. Previous assessments reported stable boreal wildfire activity up to 2014³⁴ but these findings predated the recent surge in fire frequency and intensity driven by anthropogenically induced warming and drought^{1,4,27}. Our analysis identifies a significant structural shift in 2019 ($\text{supF} = 15.9$, $p < 0.01$), marking a departure from historical norms. Following this break, the trajectories for both wet and total smoke deposition shifted toward rapid intensification (Fig. 1b), while dry deposition trends reversed from a long-term decline to an increase. This shift suggests the GrIS has entered a new regime of aerosol loading, characterized by a heightened sensitivity to escalating boreal wildfire activity.

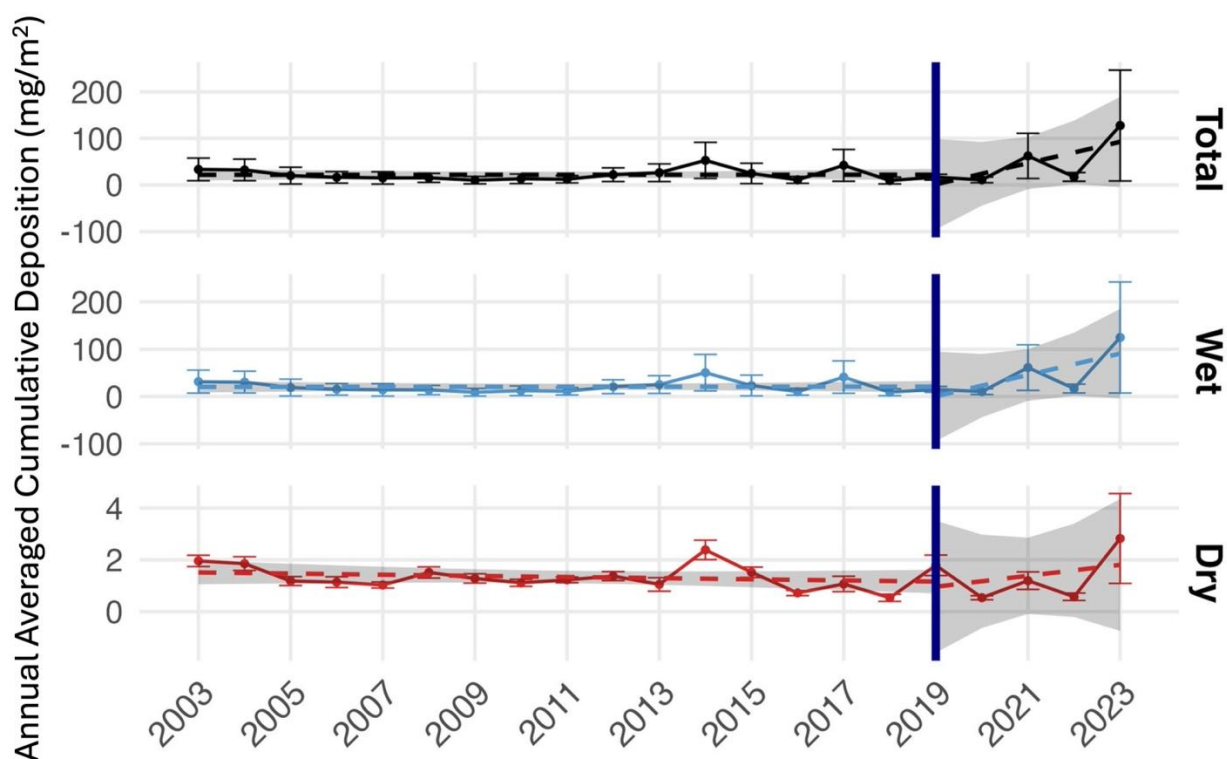


Fig. 1. Ice sheet-wide overall annual cumulative smoke deposition averaged across all transects showing changes in trend in 2019, indicated by vertical lines, from structural change analysis. Total deposition is shown in black, wet deposition in blue, and dry in red. Shaded bars indicate 95% confidence intervals of linear model predictions and bars at each point represent the standard deviation each year.

Following the 2019 structural shift, the nature of smoke deposition transitioned toward shorter, more concentrated pulses of aerosol loading. Smoke event intensity—defined as cumulative deposition per event duration—increased significantly across the majority of transects and

deposition pathways (Table ED-6). This intensification was accompanied by a nearly three-fold increase in extreme deposition events (≥ 95 th percentile). Prior to 2019, the GrIS averaged 3.5 total extreme events annually; after 2019, this frequency rose to 11.2, with similar tripling observed across both wet and dry deposition mechanisms (Fig. 1). This shift highlights a departure from chronic, low-level loading toward an episodic regime dominated by high-magnitude deposition events,

Smoke Deposition Resulting from the 2023 Canadian Wildfire Season

The 2023 Canadian wildfire season drove unprecedented smoke deposition across the GrIS, with annual cumulative values surpassing the previous 20-year average across all monitored transects (Fig. 2a–d; Table ED-4). Total smoke deposition reached $1,274.8 \text{ mg m}^{-2}$, a single-year load representing 21.6% of the cumulative deposition measured between 2003 and 2023. This impact was characterized by strong spatial heterogeneity, with the southern GrIS absorbing the brunt of the aerosol loading. The Kanger, South Central, and South transects together accounted for 67.1% of the total 2023 deposition, with the Kanger transect experiencing a 10-fold increase in wet and total deposition relative to the 20-year mean. In contrast, the northeastern region of the ice sheet exhibited less pronounced anomalies (Fig. 2c; Table ED-4), indicating that while 2023 was an anomalous year for the entire ice sheet, the southern ablation zones faced a disproportionate burden of smoke deposition.

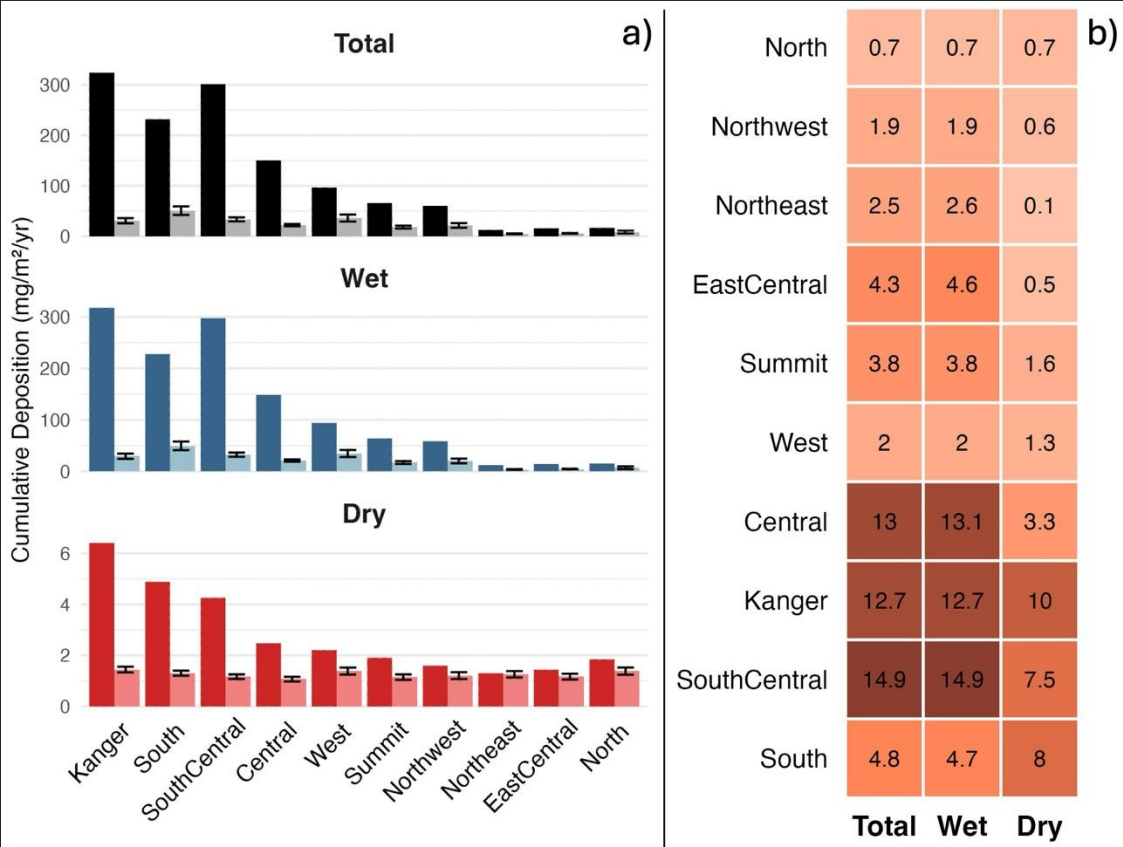
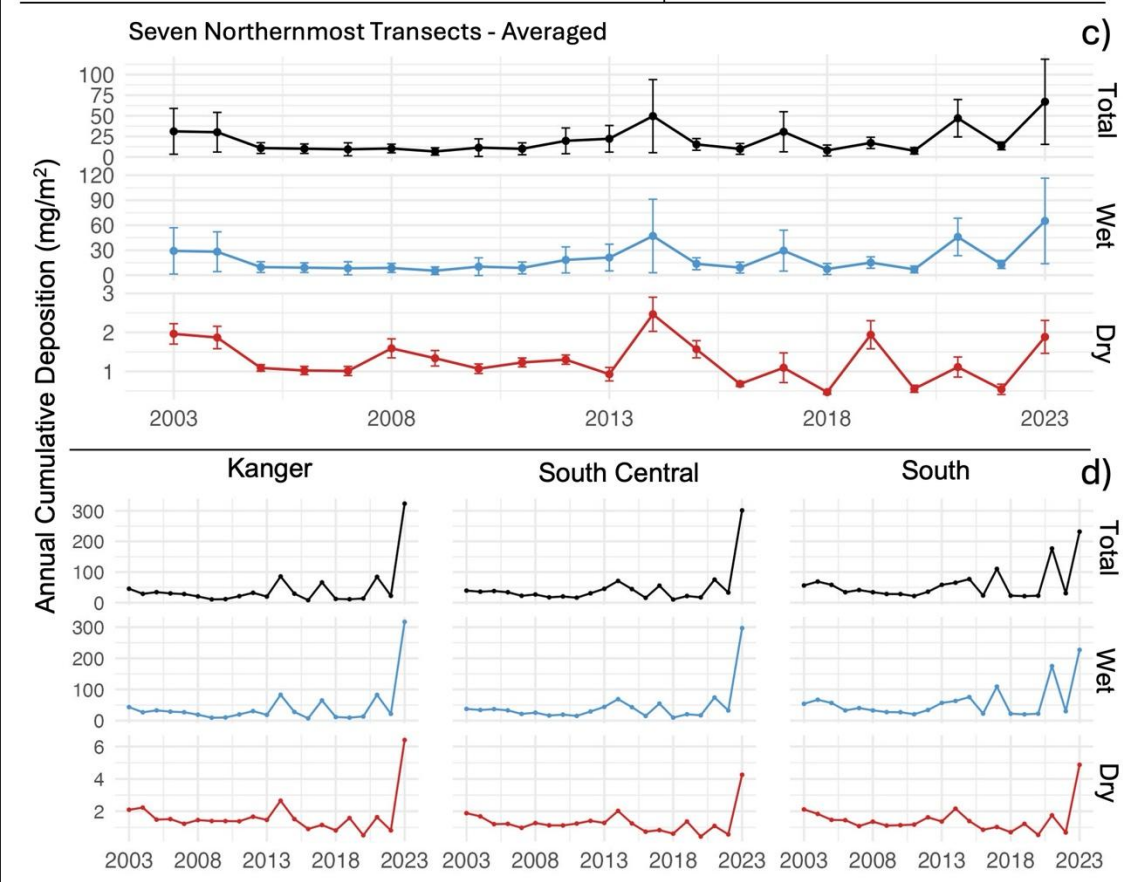


Fig. 2a-d. Cumulative smoke deposition in 2023 compared to the previous 20-year average. **a)** annual cumulative deposition ($\text{mg}/\text{m}^2/\text{yr}$) in 2023 (darker bars) compared to the average annual cumulative deposition from 2003 – 2022 (lighter bars) in each transect for each deposition mechanism; **b)** heatmap of Z-scores showing how many standard deviations total, wet, and dry deposition in 2023 deviated above the 20-year mean for each transect., **c)** annual cumulative smoke deposition averaged across the North, Northwest, Northeast, East Central, West, Summit and Central transects for each year from 2003 - 2023; **d)** annual cumulative smoke deposition in the Kanger, South Central, and South transects from 2003 – 2023.

The 2023 season was characterized by a widespread amplification of smoke loading across nearly all deposition types and transects. The frequency of 'substantial smoke days' and individual deposition events reached record highs, with statistical significance across eight of ten transects (Fig. 6b; Table ED-7). This increase in frequency was compounded by a significant surge in event intensity; smoke events in 2023 were not only more frequent but also delivered higher aerosol loads over shorter durations, particularly across the southern ice sheet (Fig. 6c; Table ED-8).

The extraordinary nature of the 2023 season is best illustrated by the clustering of extreme events ($\geq 95\text{th}$ percentile). Of all extreme wet and total deposition events identified over the 21-year study period, more than one-third (34%) occurred in 2023 alone. These extremes were heavily concentrated in the southern ablation zones; for instance, the Kanger transect recorded a single seven-day event of 83.3 mg m^{-2} , a magnitude 4.3 times higher than the multi-decadal average for extreme events (Table 1). Dry deposition followed a similar trajectory, with 2023 accounting for 22.5% of all extreme dry events since 2003. In the southern regions, individual dry deposition peaks reached 6.7 times the historical average, underscoring a regime shift toward episodic, high-magnitude loading that dominates the annual mass balance of light-absorbing particles.

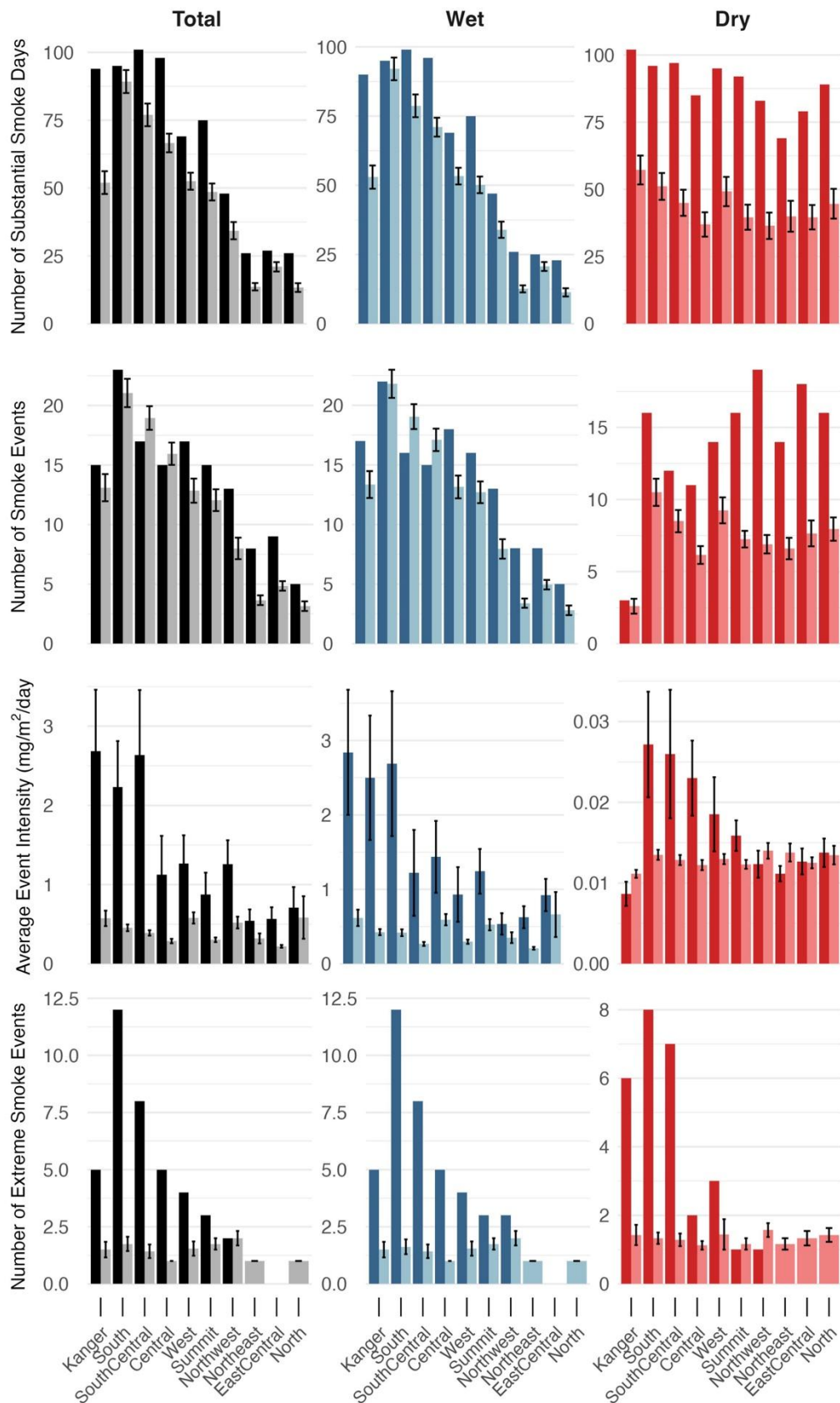


Fig. 3a-d. Smoke deposition attributes in 2023 (darker bars on left) compared to the average from 2003 – 2023 (lighter bars on right). **a)** Number of substantial smoke deposition days (exceeding baseline threshold) for each mechanism; **b)** Number of smoke events in 2023 compared to average; **c)** Average intensity of smoke events in 2023 compared to average; **d)** Number of extreme smoke events in 2023 compared to average. Lack of a bar for 2023 for Northeast, East Central, and North indicates that there were no extreme smoke events in those transects during 2023. Missing bars for the East Central transect for wet and total deposition indicates that there were no extreme smoke events in that transect between 2003 and 2023.

Drivers of Smoke Transport to the GrIS

Smoke loading across the GrIS is characterized by a robust southwest-to-northeast gradient, with the highest deposition magnitudes concentrated in the southern ablation zones (Fig. 4). This spatial asymmetry is statistically significant across total, wet, and dry deposition pathways (Kruskal-Wallis; $p < 0.001$; Table ED-3), yet the drivers of this disparity are mechanism-specific. Wet deposition exhibited the most pronounced regional clustering, with the southern and southwestern transects serving as primary depositional hotspots. In contrast, dry deposition was more homogeneous across the ice sheet, though a clear latitudinal decline toward the north persisted (Table ED-3c).

This regional loading pattern reflects preferential atmospheric transport pathways from North American sources. Satellite-derived AOD and NAAPS reanalysis confirm that the highest-magnitude deposition events are directly coupled with extreme wildfire activity in Canada (Table 1; Fig. 5a-f). The southwestern GrIS effectively acts as the primary atmospheric 'gateway' for this smoke; all five of the largest total and wet deposition events on record occurred within the three southernmost transects. The scale of this regional disparity is stark: extreme events in the southwest ($62.6\text{--}116.1\text{ mg/m}^2$) are nearly two orders of magnitude larger than the highest events recorded in the north (e.g., $\sim 1.2\text{ mg m}^{-2}$ in 2014 and 2017). These findings suggest that the southern GrIS is uniquely vulnerable to the accelerating frequency of boreal wildfires, receiving a disproportionate share of light-absorbing impurities that drive surface darkening.

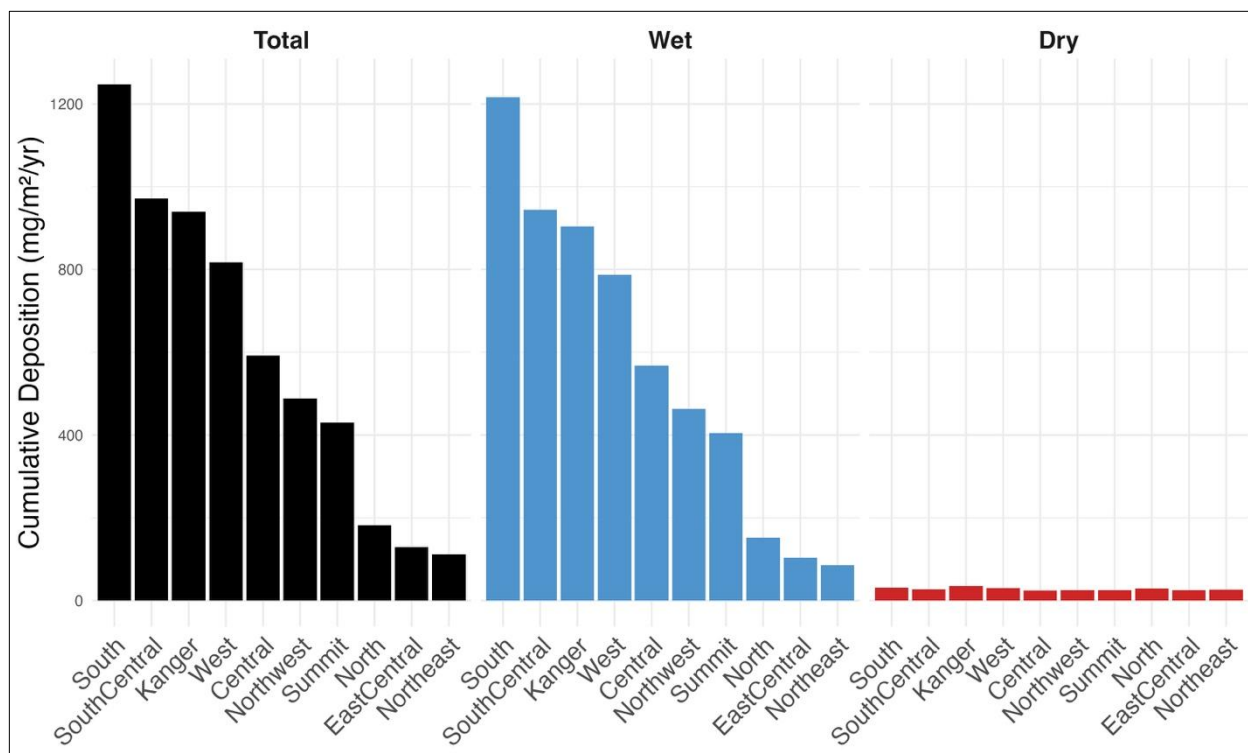


Fig. 4. Overall cumulative smoke deposition summed from 2003 – 2023 in each transect, separated by deposition mechanism.

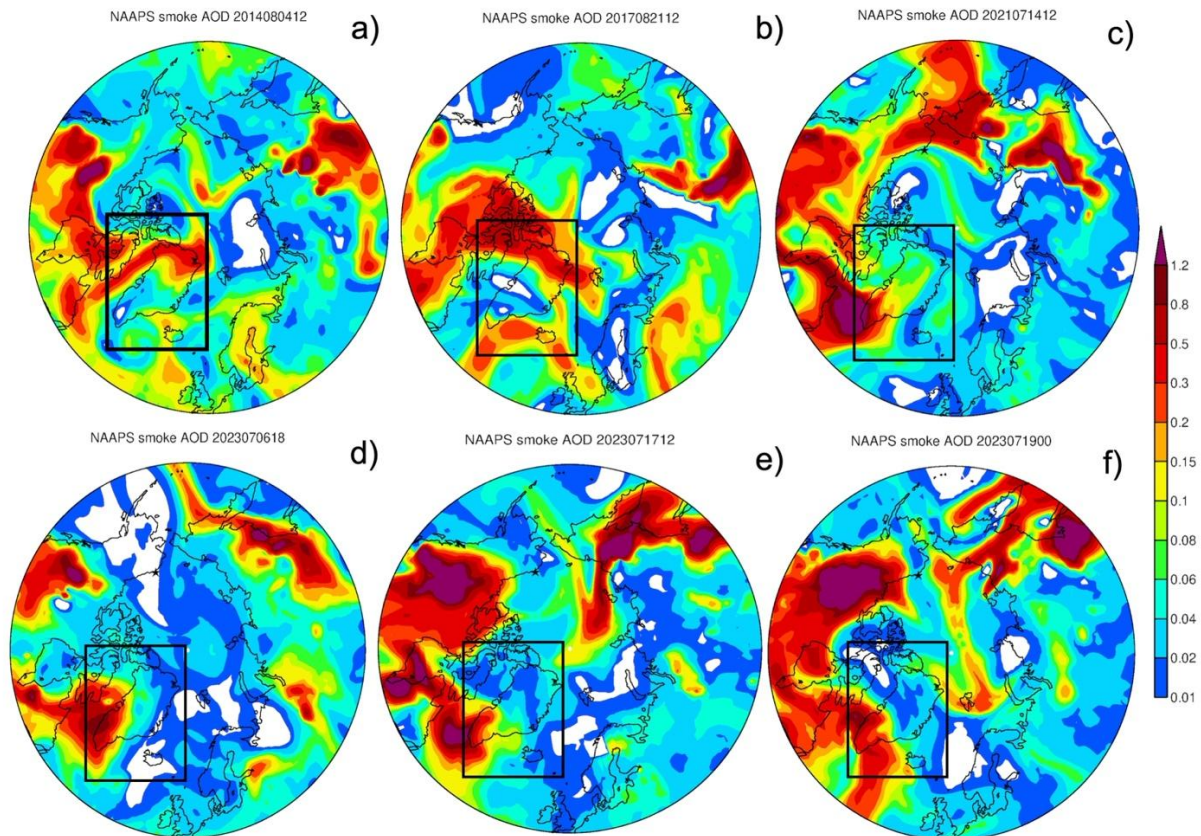


Fig. 5a-f. Smoke AOD during six of the highest extreme smoke deposition events in Greenland. Black boxes indicate the location of Greenland. **a)** smoke AOD during an extreme dry smoke event in the North transect on 2014-8-4; **b)** smoke AOD during an extreme dry event in the North transect on 2017-8-21; **c)** smoke AOD during extreme wet and total events in the South transect on 2021-8-14; **d)** smoke AOD during extreme wet and total events in the South Central transects and an extreme dry events in the Kanger and South Central transects on 2023-7-6; **e)** smoke AOD during extreme wet and total events in the Kanger and South Central transects and an extreme dry event in the Kanger transect on 2023-7-17; **f)** smoke AOD during extreme wet and total events in the Kanger and South Central transects and an extreme dry event in the Kanger transect on 2023-7-19.

To quantify the radiative impact of the 2023 season, we utilized Generalized Additive Models (GAMs) to assess the relative influence of smoke deposition and meteorological drivers on albedo variability. Model performance was highest in the southwestern ablation zone (Adjusted $R^2 = 0.83$, Deviance Explained = 84.6%; Table ED-9a), where we identified a distinct seasonal evolution in albedo drivers. While air pressure and temperature are traditionally the primary controls on surface albedo, their relative importance was surpassed by smoke deposition during critical periods of the melt season. In the early melt season (June), the immediate impact of daily dry deposition accounted for ~9% of albedo variance; however, by August, the influence of aggregated smoke loading during extreme events surged to explain 54.2% of the modeled variance (Table ED-9b).

Over the full May–September melt season, aggregated smoke deposition emerged as the single most important predictor of albedo variability in the ablation zone, contributing 30.8% to the total explained variance—exceeding the individual contributions of both air temperature and air pressure (Table ED-9b). This dominance was further amplified during the peak loading months of July and August. During this window, smoke deposition explained 46.4% of the overall albedo variance, a contribution approximately 5.3 times greater than that of air temperature (8.8%) and 3.6 times greater than air pressure (13%; Table ED-9a,b). These results suggest that in extreme wildfire years, the darkening effect of smoke aerosols can fundamentally decouple albedo decay from standard thermodynamic forcing, potentially accelerating melt rates beyond current temperature-based projections.

Discussion

Spatial Asymmetry and Atmospheric Conduits

The striking southwest-to-northeast gradient in smoke deposition observed over the last two decades underscores the role of the GrIS as a high-elevation barrier within the global atmospheric circulation (Fig. 4). Our findings indicate that the southwestern GrIS acts as a primary receptor for North American wildfire emissions, facilitated by mid-latitude westerlies and the polar jet stream^{8,35}. This regional vulnerability is further exacerbated by orographic modulation; the Western slopes drive uplift and aerosol scavenging, while the northeast remains shielded in a precipitation shadow, more frequently influenced by Eurasian air masses^{17,36,37}. The concentration of dark impurities in the southern ablation zone is particularly critical, as this region is already the most melt-sensitive portion of the ice sheet^{19,20}.

The 2019 Regime Shift: A New Era of Boreal Fire Impacts

While multi-decadal trends often mask interannual variability, our identification of a structural breakpoint in 2019 signals a fundamental shift in the cryospheric-atmospheric relationship. This transition coincides with an unprecedented intensification of boreal wildfire activity, fueled by the "hotter and drier" summers characteristic of anthropogenic warming^{1,38}. The surge in extreme fire seasons—notably 2021 and 2023—suggests that the post-2019 trajectory is not a statistical anomaly but a "new normal." With extreme fires projected to increase 50% by 2100³⁹ the GrIS is entering a regime where episodic, high-magnitude smoke loading may become a dominant driver of annual mass balance.

Mechanisms of the 2023 Extreme: Heat Domes and PyroCb Activity

The extraordinary smoke loading of 2023 was the product of a "perfect storm" of fire behavior and atmospheric physics. Persistent high-pressure "heat domes," anchored by amplified Rossby waves and phase-locking, created the ideal conditions for both extreme fire spread and stagnant atmospheric transport^{40,41}. This reflects a key tenet of Arctic Amplification: a weakened equator-to-pole temperature gradient allows for slower, more persistent weather patterns that "trap" smoke plumes over the ice sheet^{25,42}. Furthermore, the 2023 season demonstrated the power of fire-induced weather; the 142 recorded pyrocumulonimbus (pyroCb) events represent a massive injection of aerosols into the upper troposphere and lower stratosphere.⁴³ These high-altitude injections bypass low-level removal processes, ensuring high-efficiency long-range transport and making the GrIS a direct downwind victim of boreal fire intensity.^{44–46}

Decoupling Albedo from Temperature: A Critical Feedback

Under the extreme smoke conditions of 2023, aerosol deposition emerged as the primary predictor of albedo decay in the southwestern ablation zone, effectively decoupling surface darkening from standard thermodynamic forcing. Our findings reveal that during the peak melt period (July–August), aggregated smoke loading explained 46.4% of albedo variance—nearly five times the influence of air temperature (8.8%). This represents a significant exacerbation of the established melt-albedo feedback^{47,48,49}. As anthropogenic warming intensifies boreal fire regimes, the resulting smoke-driven darkening increases the ice sheet’s sensitivity to solar radiation, accelerating melt even in the absence of local temperature anomalies. This mechanism is particularly critical in the southwestern GrIS, where the expansion of bare ice and the accumulation of dark impurities have already primed the region for enhanced melt-sensitivities.

Conclusion

While the 1° resolution of the NAAPS reanalysis and the diagnostic nature of Generalized Additive Models (GAMs) involve inherent spatial smoothing and statistical constraints, the convergence of modeling, meteorological analysis, and ground-based observations provides compelling evidence of a fundamental regime shift. Our results demonstrate that wildfire smoke is no longer a secondary atmospheric constituent but a primary driver of GrIS surface darkening. As wildfire seasons continue to break historical records, integrating these episodic smoke events into attributable radiative forcing and melt-modeling is a prerequisite for accurate projections of ice-sheet stability and global sea-level rise.

Table 1. Attributes of the top five smoke deposition events with the highest cumulative smoke deposition for wet, dry, and total deposition mechanisms.

Transect	Year	Start Date	End Date	Duration (Days)	Cumulative Deposition (mg/m ²)
Total					
South	2021	7/14/21	7/15/21	2	116.06
Kanger	2023	7/17/23	7/23/23	7	83.28
South Central	2023	7/17/23	7/21/23	5	79.74
South Central	2023	7/5/23	7/7/23	3	73.23
Kanger	2021	7/13/21	7/15/21	3	62.75
Wet					
South	2021	7/14/21	7/15/21	2	115.46
Kanger	2023	7/17/23	7/23/23	7	82.09
South Central	2023	7/17/23	7/21/23	5	79.06
South Central	2023	7/5/23	7/7/23	3	72.43
Kanger	2021	7/13/21	7/15/21	3	62.61
Dry					
Kanger	2023	7/4/23	7/9/23	6	2.04
Kanger	2023	7/16/23	7/23/23	8	1.25
North	2014	8/3/14	8/7/14	5	1.20
North	2017	8/20/17	8/23/17	4	1.16
South Central	2023	7/6/23	7/9/23	4	1.14

Methods

Data

NAAPS-RA v1 Smoke Deposition Flux Data

To assess spatiotemporal patterns and across the GrIS from 2003 – 2023, and to compare smoke deposition across the GrIS in 2023 to the previous 20 years, daily smoke deposition fluxes from the Navy Aerosol Analysis and Prediction System reanalysis version 1 (NAAPS-RA v1) model were used (hereafter referred to as NAAPS). NAAPS is a global aerosol reanalysis model developed by the U.S. Naval Research Laboratory that simulates the life cycle of several aerosol types, including smoke from biomass burning, anthropogenic and biogenic fine aerosols, dust and sea salt, by explicitly modeling emission, transport, and removal via wet and dry mechanisms^{50–52}. NAAPS was first implemented as an operational forecasting tool, but has since been refined into a reanalysis model (NAAPS-RA v1), which incorporates quality-controlled aerosol optical depth (AOD) observations from the moderate resolution imaging spectroradiometer (MODIS) and the multi-angle imaging spectroradiometer (MISR;^{50–52}. Meteorological parameters are provided by the Navy Global Environmental Model (NavGEM;⁵³ and biomass burning emissions are parameterized using the Fire Locating and Modeling of Burning Emissions (FLAMBE) system;⁵⁴ which relies on MODIS active fire detections.

The NAAPS-RA v1 data spans from 2003 to the present at a 1°x1° spatial resolution at 6-hourly time steps and 25 vertical levels^{50–52}. For this analysis, we used daily wet, dry, and total (wet + dry) smoke deposition fluxes, defined as the 24-hour cumulative flux of biomass burning aerosols to the surface, given in mg/m²/day. The model assumes a uniform deposition flux across each 1° grid cell and does not account for surface heterogeneity within the grid cell.

PROMICE and GC-Net Automatic Weather Station Data

The Greenland Climate Network (GC-Net) was established in 1995, with 31 AWSs across the GrIS⁵⁵. In 2007, the Programme for the Monitoring of the Greenland Ice Sheet (PROMICE) built upon the observational capacity of GC-Net, operating 25 AWSs primarily in the ablation zone of the GrIS⁵⁶. Together, PROMICE and GC-Net provide the longest record of observed atmospheric and surface conditions, recording hourly measurements at point locations across the GrIS. Eighteen AWSs located within 1° x 1° NAAPS grid cells intersecting the defined transects were included in the analysis (Figure SI-1). Detailed attributes of each PROMICE/GC-Net station used for this analysis can be found in Table SI-3.

Albedo and meteorological measurements from the PROMICE and GC-Net AWSs were used to assess the relative influence of wildfire smoke deposition and other environmental variables on surface albedo variability. First, only days with NAAPS-modeled dry smoke deposition without any wet deposition were isolated because dry deposition occurs independently of precipitation and can directly darken the snow or ice surface, producing a more immediate effect on surface albedo⁵⁷.

During days with dry smoke deposition and no wet deposition, hourly measurements of shortwave broadband albedo ($\lambda = 300\text{--}2800\text{ nm}$), air pressure (hPa), air temperature ($^{\circ}\text{C}$), relative humidity (adjusted for saturation over ice in subfreezing conditions; %), and wind speed (m/s) from the selected PROMICE and GC-Net stations were downloaded from the GEUS THREDDS Data Server (Version 26;⁵⁸). For stations equipped with both upper and lower measurement booms, the two observations were averaged to produce a single representative value. A daily mean value for each variable was calculated using observations between 10:00 and 15:00 Coordinated Universal Time (UTC) to minimize aggregation errors associated with high solar zenith angles and gaps in the albedo record. Albedo values at the AWSs are derived from shortwave radiation measurements and are only computed when the solar zenith angle is less than 70° (Lund, M. C., personal communication, August 5, 2025), making midday observations the most reliable for daily aggregation. Additional quality control filtering was applied to remove unrealistic albedo values. Observations greater than 0.98 or less than 0.10 were excluded, following a similar approach to Nishimura et al. (2023) who applied albedo range tests of 0.1–0.95 to Greenland AWS records to remove values likely affected by aggregation errors or extreme solar zenith angles. The resulting daily AWS datasets were merged with NAAPS dry smoke deposition fluxes for the corresponding 1° grid cells containing each station (Figure SI-1).

Study Area Selection

Ten transects consisting of 1° latitude x 1° longitude tiles, matching the resolution of NAAPS-RA, were selected across the GrIS (Figure SI-1). Transects were chosen to capture spatial variation in smoke deposition across the GrIS, and tiles were preferentially selected that intersect the locations of PROMICE / GC-Net automatic weather stations and lie on ice-covered surfaces. Detailed attributes of each transect can be found in Table SI-2.

Daily wet, dry, and total smoke deposition fluxes were extracted from the NAAPS model using the centroid coordinates (Table SI-2) of each of the individual tiles in Figure SI-1 between 01/01/2003 and 12/31/2023. For fair inter-transect comparisons, and to account for differing numbers of tiles among transects, daily smoke deposition fluxes from individual tiles were aggregated by averaging values from each tile across the whole transect. The daily transect-averaged smoke deposition fluxes from each transect were used to perform a series of statistical analyses to analyze spatial and temporal patterns of smoke deposition over the 20-year study period and to compare deposition in 2023 to the previous 20-year average.

Statistical Analysis

All statistical analyses were conducted in R version 2024.09.0+375 (R Core Team, 2023). Data was assessed for normality and homogeneity of variance using Shapiro-Wilks and Levene's tests, respectively, for all statistical tests. If assumptions required for parametric testing were not met, non-parametric tests were used. Statistical significance for all tests was defined as $\alpha < 0.05$.

Spatial Variation in Smoke Deposition

To assess spatial differences in smoke deposition fluxes among transects, a non-parametric Kruskal-Wallis test was performed to determine whether median deposition values differed significantly among the ten transects. When significant overall differences were detected, post-hoc pairwise comparisons were conducted using Dunn's test with Bonferroni corrections to control for family-wise error rates to determine which transects had significant differences in median deposition for each mechanism. Analyses were performed using daily averaged smoke deposition fluxes for each mechanism across each transect from 2003 – 2023.

Calculating a Baseline Smoke Deposition Threshold for Substantial Smoke Deposition

Most daily smoke deposition values across the GrIS were very low, and effectively zero (Table ED-1), so a threshold value for detecting days with substantial smoke deposition fluxes was necessary. To define a consistent, ice sheet-wide threshold value, daily total, wet, and dry deposition data from all transects were analyzed collectively. Combining data across transects allowed for the derivation of a single ice sheet-wide threshold, preventing artificial inflation of smoke event detection in low-deposition transects that would occur if per-transect thresholds were used.

Because smoke deposition on the GrIS was found to be highest during the Northern Hemisphere wildfire season, a subset of data between May and September were used to reduce annual variability and focus on the period of interest to define a threshold value. Distributional summaries showed substantial right skew across all deposition types for all mechanisms, demonstrating that most deposition days had negligible deposition, and that mean-based thresholds would be inappropriate due to the skewed nature of the data (Table ED-1). Therefore, a percentile-based method was used to define a threshold value for baseline smoke deposition levels in order to identify days with substantial smoke deposition. The threshold was set at the 75th percentile (Q3) for each deposition type (Total = 0.043 mg/m²/day; Wet = 0.035 mg/m²/day; Dry = 0.006 mg/m²/day) during the period from May - September, 2003 - 2023, corresponding to the upper quartile of deposition days during the smoke season. The threshold value was then applied to the full time period (all months, 2003 – 2023) for each deposition type. This approach yielded approximately 13% of all daily values above the threshold across all months for each deposition mechanism, effectively distinguishing higher-deposition days from very low background levels.

Days with smoke deposition exceeding the Q3 threshold were classified as substantial smoke deposition days. Smoke events were defined as periods when the threshold value was exceeded for two or more consecutive days. The identified days and events were used for subsequent analysis.

Extreme Smoke Deposition

For each smoke deposition mechanism (wet, dry, total), days exceeding the baseline threshold value were first identified using the methods described above. Within the subset of

days exceeding the threshold, extremely high smoke deposition days were identified as those at or above the 95th percentile of that subset's distribution for each deposition mechanism, following a similar approach as ⁵¹ for detecting extreme AOD events. Extreme smoke deposition events were then defined as periods consisting of two or more consecutive days with daily deposition above the 95th percentile.

Smoke Transport to the GrIS During Extreme Smoke Events

NAAPS smoke AOD maps at 6-hourly timesteps were used to track the movement of biomass burning smoke from the source region to the GrIS and confirm the areas of highest smoke deposition during extreme smoke events. The top five extreme smoke deposition events with the highest cumulative smoke deposition for each mechanism were identified, and then 6-hourly smoke AOD maps during each smoke event and the 10 days prior to each event were analyzed to determine the origin and transport of the smoke to the GrIS.

Temporal Trends in Smoke Deposition

Temporal trends in various smoke deposition attributes were evaluated for each transect over the full study period (2003–2023). Annual cumulative deposition and the annual number of extreme smoke deposition events were analyzed using non-parametric Mann-Kendall trend tests to detect monotonic trends over time. Additional smoke deposition characteristics - the annual number of substantial smoke deposition days, the annual number of smoke events, average annual event duration and intensity, and the annual start date and duration of the smoke season - were assessed using bivariate linear regressions.

Structural Change Analysis

To identify potential temporal shifts in long-term smoke deposition trends, a structural change analysis was conducted using the *strucchange* package in R ⁶⁰. Separate analyses were performed for total, wet, and dry annual cumulative smoke deposition time series. For each deposition type, a simple linear regression model of annual cumulative deposition (averaged across all transects) as a function of year was fitted. The *Fstats* function was then applied to these models to compute a sequence of F-statistics (also known as Quandt Likelihood Ratio statistics) for every possible breakpoint within the time series.

The *breakpoints* function was then used to estimate the most likely breakpoint (year) at which the structural change occurred, based on the maximum F-statistic. The overall significance of the detected structural change was assessed using the *sctest* function with the “supF” test type, which tests the null hypothesis of no structural change against the alternative of at least one structural break. The identified breakpoint year was then used as a natural division in the data to assess differences in deposition trends before and after the structural change for each deposition type.

The structural change analysis identified a significant breakpoint in the trend of annual cumulative smoke deposition in 2019. The data was then broken into two periods: pre-2019 and post-2019. Linear regressions were conducted separately for each period to evaluate trends in annual cumulative deposition before and after 2019. To assess differences in smoke deposition between periods, Wilcoxon rank-sum tests were applied to compare the distributions of annual smoke deposition characteristics (number of substantial smoke deposition days, smoke events, event duration, event intensity, number of extreme days and events, start date, and season duration). Because the Wilcoxon rank-sum test compares medians rather than means, the direction of change between periods was determined by examining differences in group medians.

Comparing Smoke Deposition in 2023 to the Previous 20-Year Average

The data were split into two periods: 2003 – 2022, and 2023 alone. To evaluate the magnitude of smoke deposition in 2023 relative to the previous 20 years (2003 - 2022), multiple statistical approaches were used. For each transect, a one-sample Student's t-test was used to compare the number of days exceeding the baseline in 2023 and the number of smoke events in 2023 to the previous 20-year mean, as well as the number of extremely high smoke days in both periods. Event duration and intensity in 2023 were compared to the 2003 - 2022 averages using Wilcoxon rank-sum tests. Z-scores were calculated for the number of extreme smoke events in 2023 to indicate the degree of deviation from the long-term average.

Generalized Additive Models and Relative Importance Analyses

To evaluate the influence of dry smoke deposition relative to other environmental variables on observed albedo variability, we applied Generalized Additive Models (GAMs) using the *mgcv* package⁶¹ with a Gaussian error distribution and identity link. Continuous predictors were represented using thin-plate regression splines with a basis dimension of $k = 10$ for each smooth term, and smoothing parameters were estimated using restricted maximum likelihood (REML).

The response variable in each model was daily shortwave broadband albedo ($\lambda = 300\text{--}2800$ nm) during periods when dry smoke deposition occurred without concurrent wet deposition. Predictor variables included daily dry smoke deposition ($\text{mg}/\text{m}^2/\text{day}$), aggregated dry smoke deposition during smoke events (mg/m^2), air pressure (hPa), air temperature ($^{\circ}\text{C}$), relative humidity (adjusted for saturation over ice in subfreezing conditions; %), wind speed (m/s), and day of the year (DOY). Aggregated dry smoke deposition was calculated by summing daily dry deposition between wet deposition events, representing the accumulation of BC aerosols during precipitation-free periods.

For spatial comparisons, AWS sites were grouped into three broad geographic regions of the GrIS: Northwest ($n = 4$), Northeast ($n = 4$), and South ($n = 10$). In addition to these regional groupings, all stations were also analyzed together as a single dataset (All AWS; $n = 18$). To examine differences related to surface mass balance (SMB) regimes, the same stations were further classified into accumulation ($n = 13$) and ablation ($n = 5$) zones (Table ED-2). Identically

parameterized models were fitted separately for each region and SMB regime using data from the full 2003–2023 record as well as for the year 2023 alone. Within each time period, analyses were conducted for several temporal subsets, including the full smoke season (May–September), the peak melt period (July–August), and individual months between May and September.

To quantify the relative influence of each predictor variable in the GAMs, we performed a variance decomposition analysis using the *gam.hp* package in R⁶², which applies hierarchical partitioning to GAM outputs. This approach separates the model R^2 into the independent contribution of each predictor, allowing the relative importance of variables to be compared within each model. The results are expressed as the percentage of total explained variance in albedo attributed to each predictor. These percentages were used to determine which variables contributed most strongly to albedo variability and to compare their relative influence across regions, SMB zones, and time periods.

Data Availability

Data and code used to produce these findings are available on Zenodo (private reviewer link).

References

1. Abatzoglou, J. T., Williams, A. P., Boschetti, L., Zubkova, M. & Kolden, C. A. Global patterns of interannual climate–fire relationships. *Glob. Change Biol.* **24**, 5164–5175 (2018).
2. Intergovernmental Panel On Climate Change. *Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. (Cambridge University Press, 2022). doi:10.1017/9781009157988.
3. Jain, P., Wang, X. & Flannigan, M. D. Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. *Int. J. Wildland Fire* **26**, 1009–1020 (2017).
4. Jones, M. W. *et al.* Global and Regional Trends and Drivers of Fire Under Climate Change. *Rev. Geophys.* **60**, e2020RG000726 (2022).

5. Sokolik, I. N., Soja, A. J., DeMott, P. J. & Winker, D. Progress and Challenges in Quantifying Wildfire Smoke Emissions, Their Properties, Transport, and Atmospheric Impacts. *J. Geophys. Res. Atmospheres* **124**, 13005–13025 (2019).
6. Xian, P. *et al.* Arctic spring and summertime aerosol optical depth baseline from long-term observations and model reanalyses – Part 1: Climatology and trend. *Atmospheric Chem. Phys.* **22**, 9915–9947 (2022).
7. Evangeliou, N. *et al.* Open fires in Greenland in summer 2017: transport, deposition and radiative effects of BC, OC and BrC emissions. *Atmospheric Chem. Phys.* **19**, 1393–1411 (2019).
8. Law, K. S. *et al.* Arctic Air Pollution: New Insights from POLARCAT-IPY. *Bull. Am. Meteorol. Soc.* **95**, 1873–1895 (2014).
9. McCarty, J. L. *et al.* Reviews and syntheses: Arctic fire regimes and emissions in the 21st century. *Biogeosciences* **18**, 5053–5083 (2021).
10. Stohl, A. *et al.* Pan-Arctic enhancements of light absorbing aerosol concentrations due to North American boreal forest fires during summer 2004. *J. Geophys. Res. Atmospheres* **111**, 2006JD007216 (2006).
11. Bond, T. C. *et al.* Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res. Atmospheres* **118**, 5380–5552 (2013).
12. Flanner, M. G., Zender, C. S., Randerson, J. T. & Rasch, P. J. Present-day climate forcing and response from black carbon in snow. *J. Geophys. Res. Atmospheres* **112**, (2007).
13. Hadley, O. L. & Kirchstetter, T. W. Black-carbon reduction of snow albedo. *Nat. Clim. Change* **2**, 437–440 (2012).
14. Warren, S. G. Optical properties of snow. *Rev. Geophys.* **20**, 67 (1982).

15. Skiles, S. M., Flanner, M., Cook, J. M., Dumont, M. & Painter, T. H. Radiative forcing by light-absorbing particles in snow. *Nat. Clim. Change* **8**, 964–971 (2018).
16. Khan, A. L. *et al.* Dissolved black carbon in the global cryosphere: Concentrations and chemical signatures. *Geophys. Res. Lett.* **44**, 6226–6234 (2017).
17. Box, J. E. *et al.* Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. *The Cryosphere* **6**, 821–839 (2012).
18. Enderlin, E. M. *et al.* An improved mass budget for the Greenland ice sheet. *Geophys. Res. Lett.* **41**, 866–872 (2014).
19. Ryan, J. C. *et al.* Dark zone of the Greenland Ice Sheet controlled by distributed biologically-active impurities. *Nat. Commun.* **9**, 1065 (2018).
20. Tedstone, A. J. *et al.* Dark ice dynamics of the south-west Greenland Ice Sheet. *The Cryosphere* **11**, 2491–2506 (2017).
21. Keegan, K. M., Albert, M. R., McConnell, J. R. & Baker, I. Climate change and forest fires synergistically drive widespread melt events of the Greenland Ice Sheet. *Proc. Natl. Acad. Sci.* **111**, 7964–7967 (2014).
22. Tedstone, A. J. *et al.* Algal growth and weathering crust state drive variability in western Greenland Ice Sheet ice albedo. *The Cryosphere* **14**, 521–538 (2020).
23. Wientjes, I. G. M. *et al.* Carbonaceous particles reveal that Late Holocene dust causes the dark region in the western ablation zone of the Greenland ice sheet. *J. Glaciol.* **58**, 787–794 (2012).
24. Aschwanden, A. *et al.* Contribution of the Greenland Ice Sheet to sea level over the next millennium. *Sci. Adv.* **5**, eaav9396 (2019).

25. Serreze, M. C. & Barry, R. G. Processes and impacts of Arctic amplification: A research synthesis. *Glob. Planet. Change* **77**, 85–96 (2011).
26. Jolly, W. M. *et al.* Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat. Commun.* **6**, 7537 (2015).
27. Richardson, D. *et al.* Global increase in wildfire potential from compound fire weather and drought. *Npj Clim. Atmospheric Sci.* **5**, 23 (2022).
28. Bush, E. & Lemmen, D. S. *Canada's Changing Climate Report*.
<https://changingclimate.ca/CCCR2019/> (2019).
29. Jain, P. *et al.* Drivers and Impacts of the Record-Breaking 2023 Wildfire Season in Canada. *Nat. Commun.* **15**, 6764 (2024).
30. Zhang, S., Solomon, S., Boone, C. D. & Taha, G. Investigating the vertical extent of the 2023 summer Canadian wildfire impacts with satellite observations. *Atmospheric Chem. Phys.* **24**, 11727–11736 (2024).
31. Lopez, N. Copernicus: Canada produced 23% of the global wildfire carbon emissions for 2023 | Copernicus. <https://atmosphere.copernicus.eu/copernicus-canada-produced-23-global-wildfire-carbon-emissions-2023> (2023).
32. Khan, A. L., Xian, P. & Schwarz, J. P. Black carbon concentrations and modeled smoke deposition fluxes to the bare-ice dark zone of the Greenland Ice Sheet. *The Cryosphere* **17**, 2909–2918 (2023).
33. Thomas, J. L. *et al.* Quantifying black carbon deposition over the Greenland ice sheet from forest fires in Canada. *Geophys. Res. Lett.* **44**, 7965–7974 (2017).
34. Tedesco, M. *et al.* The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100). *The Cryosphere* **10**, 477–496 (2016).

35. Paugam, R., Wooster, M., Freitas, S. & Val Martin, M. A review of approaches to estimate wildfire plume injection height within large-scale atmospheric chemical transport models. *Atmospheric Chem. Phys.* **16**, 907–925 (2016).
36. Bales, R. C. *et al.* Annual accumulation for Greenland updated using ice core data developed during 2000–2006 and analysis of daily coastal meteorological data. *J. Geophys. Res. Atmospheres* **114**, 2008JD011208 (2009).
37. Stohl, A. *et al.* Pan-Arctic enhancements of light absorbing aerosol concentrations due to North American boreal forest fires during summer 2004. *J. Geophys. Res. Atmospheres* **111**, 2006JD007216 (2006).
38. Jones, M. W. *et al.* Global and Regional Trends and Drivers of Fire Under Climate Change. *Rev. Geophys.* **60**, e2020RG000726 (2022).
39. United Nations Environmental Programme. Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires - A Rapid Response Assessment. <https://wedocs.unep.org/items/5d3e5267-17bd-4b06-9964-494dd01f7791> (2022).
40. Coumou, D., Petoukhov, V., Rahmstorf, S., Petri, S. & Schellnhuber, H. J. Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. *Proc. Natl. Acad. Sci.* **111**, 12331–12336 (2014).
41. Hu, Y., Yue, X. & Tian, C. Climatic drivers of the Canadian wildfire episode in 2023. *Atmospheric Ocean. Sci. Lett.* **17**, 100483 (2024).
42. Francis, J. A. & Vavrus, S. J. Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.* **39**, 2012GL051000 (2012).
43. Khaykin, S. *et al.* Stratospheric impact of the anomalous 2023 Canadian wildfires: the two vertical pathways of smoke. *Atmospheric Chem. Phys.* **25**, 14551–14571 (2025).

44. Fromm, M. *et al.* The Untold Story of Pyrocumulonimbus. *Bull. Am. Meteorol. Soc.* **91**, 1193–1210 (2010).
45. Peterson, D. A. *et al.* Wildfire-driven thunderstorms cause a volcano-like stratospheric injection of smoke. *Npj Clim. Atmospheric Sci.* **1**, 30 (2018).
46. Fromm, M. *et al.* Pyro-cumulonimbus injection of smoke to the stratosphere: Observations and impact of a super blowup in northwestern Canada on 3–4 August 1998. *J. Geophys. Res. Atmospheres* **110**, 2004JD005350 (2005).
47. Stroeve, J., Box, J. E., Wang, Z., Schaaf, C. & Barrett, A. Re-evaluation of MODIS MCD43 Greenland albedo accuracy and trends. *Remote Sens. Environ.* **138**, 199–214 (2013).
48. Shimada, R., Takeuchi, N. & Aoki, T. Inter-Annual and Geographical Variations in the Extent of Bare Ice and Dark Ice on the Greenland Ice Sheet Derived from MODIS Satellite Images. *Front. Earth Sci.* **4**, (2016).
49. Ryan, J. C. *et al.* Greenland Ice Sheet surface melt amplified by snowline migration and bare ice exposure. *Sci. Adv.* **5**, eaav3738 (2019).
50. Lynch, P. *et al.* An 11-year global gridded aerosol optical thickness reanalysis (v1.0) for atmospheric and climate sciences. *Geosci. Model Dev.* **9**, 1489–1522 (2016).
51. Xian, P. *et al.* Arctic spring and summertime aerosol optical depth baseline from long-term observations and model reanalyses – Part 2: Statistics of extreme AOD events, and implications for the impact of regional biomass burning processes. *Atmospheric Chem. Phys.* **22**, 9949–9967 (2022).
52. Xian, P. *et al.* Arctic spring and summertime aerosol optical depth baseline from long-term observations and model reanalyses – Part 1: Climatology and trend. *Atmospheric Chem. Phys.* **22**, 9915–9947 (2022).

53. Hogan, T. *et al.* The Navy Global Environmental Model. *Oceanography* **27**, 116–125 (2014).
54. Reid, J. S. *et al.* Global Monitoring and Forecasting of Biomass-Burning Smoke: Description of and Lessons From the Fire Locating and Modeling of Burning Emissions (FLAMBE) Program. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2**, 144–162 (2009).
55. Vandecrux, B. *et al.* The historical Greenland Climate Network (GC-Net) curated and augmented level-1 dataset. *Earth Syst. Sci. Data* **15**, 5467–5489 (2023).
56. Fausto, R. S. *et al.* Programme for Monitoring of the Greenland Ice Sheet (PROMICE) automatic weather station data. *Earth Syst. Sci. Data* **13**, 3819–3845 (2021).
57. Beres, N. D. & Moosmüller, H. Apparatus for dry deposition of aerosols on snow. *Atmospheric Meas. Tech.* **11**, 6803–6813 (2018).
58. How, P. *et al.* PROMICE and GC-Net automated weather station data in Greenland. GEUS Dataverse <https://doi.org/10.22008/FK2/IW73UU> (2022).
59. Nishimura, M. *et al.* Quality-controlled meteorological datasets from SIGMA automatic weather stations in northwest Greenland, 2012–2020. *Earth Syst. Sci. Data* **15**, 5207–5226 (2023).
60. Zeileis, A., Leisch, F., Hornik, K. & Kleiber, C. **strucchange** : An R Package for Testing for Structural Change in Linear Regression Models. *J. Stat. Softw.* **7**, (2002).
61. Wood, S. N. *Generalized Additive Models: An Introduction with R.* (Chapman and Hall/CRC, 2017). doi:10.1201/9781315370279.
62. Lai, J., Tang, J., Li, T., Zhang, A. & Mao, L. Evaluating the relative importance of predictors in Generalized Additive Models using the gam.hp R package. *Plant Divers.* **46**, 542–546 (2024).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [NCCTS2023ExtendedData.docx](#)
- [NCCTS2023SupplementaryInfo.docx](#)