

GeoAI-based Analysis of Wildfire Clusters and Smoke Impacts in the Northern Hemisphere



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Background & Motivation

Intensifying Arctic Wildfires

- Fire counts in the Arctic growing at +5.08%/yr.
- Record events in 2019 (191K fires) and 2021 (299K fires) in North America and Siberia.

Unprecedented Aerosol Anomalies

- Arctic AOD surged to 5× the historical average since 2018.
- Smoke transported from mid-latitudes increasingly reaches polar regions.

Arctic Amplification & Climate Change

- Summer temperatures in Arctic Siberia/Sakha were ~5K above 19-year average in 2019 & 2021, extending fire seasons and intensifying smoke.

Research Gap

Despite evidence of wildfire–aerosol linkages, the **spatial-temporal clustering patterns** of wildfire events and **GeoAI-driven predictive modeling** of future smoke trajectories remain largely underexplored.

25 yrs

2000–2024
Study Period

5×

Max AOD
Anomaly

+5%

Arctic Fire
Growth/yr

Research Objectives

01 Characterize Wildfire Cluster Dynamics

Analyze spatial-temporal clustering of wildfire events across the Northern Hemisphere (2000–2024) using satellite fire data, DBSCAN clustering, and kernel density estimation (KDE)

02 Assess Atmospheric Smoke & AOD Impacts

Integrate aerosol optical depth (AOD) from MODIS/AERONET and CALIPSO vertical profiles to trace wildfire smoke transport, dispersion patterns, and aerosol radiative forcing

03 Develop GeoAI Predictive Framework

Build deep learning models (CNN + LSTM) to predict future wildfire cluster trajectories and smoke plume spread under varying climatic scenarios

04 Provide Environmental Risk Insights

Deliver actionable frameworks for wildfire-smoke interaction assessment, supporting environmental risk management and policy formulation under a warming climate

Study Area & Multi-Source Data

Northern Hemisphere (0°–90°N) | 2000–2024 | North America & Eurasia Focus

Earth Observing Satellites (MODIS/VIIRS)

Active fire locations
AOD @ 550 nm (1°×1°)
Fire Radiative Power (FRP)
Terra & Aqua (2000–2024)

Ground-based Sun-sky radiometer (AERONET)

13+ Arctic stations
Ground-based AOD
Level 2.0, Version 3.0
2000–2024

Space-borne Lidar (CALIOP/CALIPSO)

Aerosol vertical profiles
532 nm / 1064 nm
Level 2 v4.51
Extinction coefficients

Meteorology Reanalysis (MERRA-2)

Reanalysis: T2M, SLP
Wind vectors @700 hPa
SW Aerosol Radiative
Forcing (SWARF)

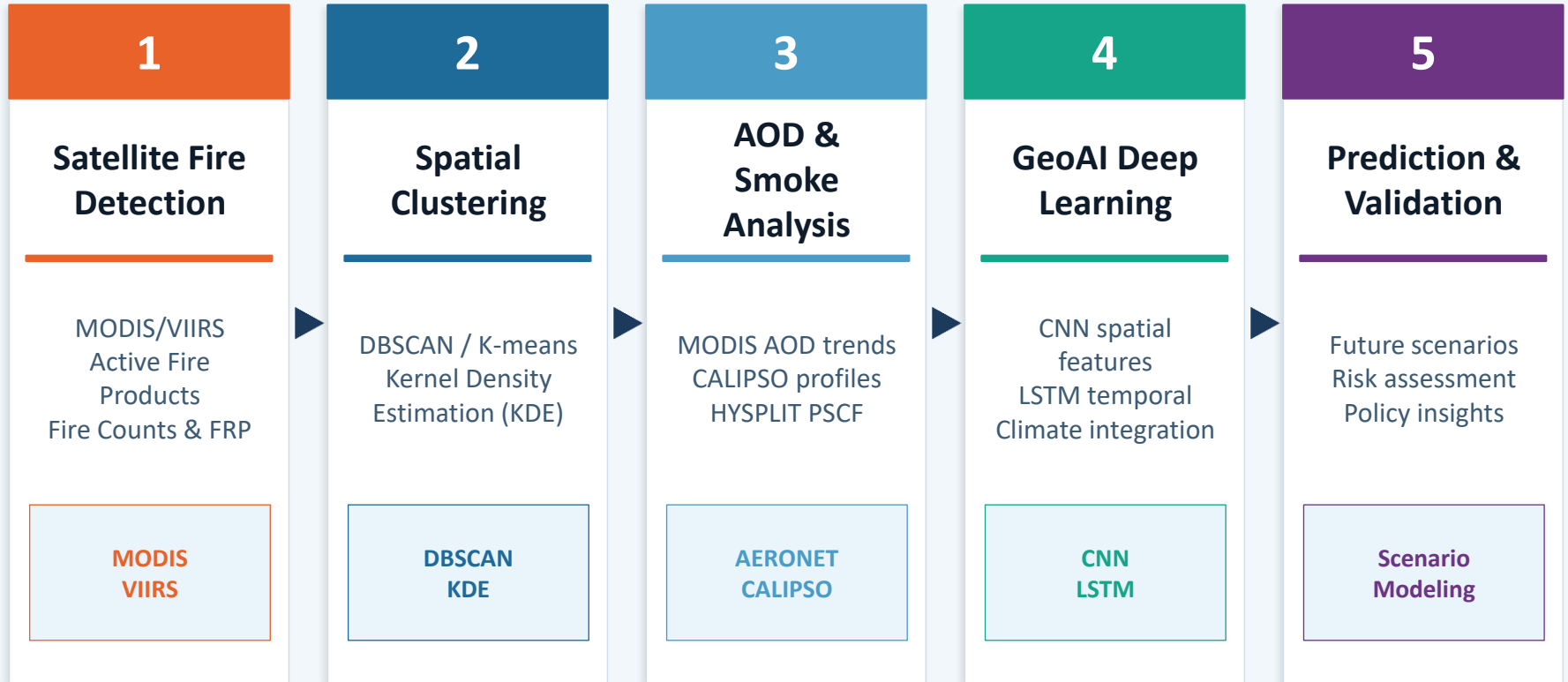
Trajectory model (HYSPLIT)

120-hr backward
trajectories
Potential Source
Contrib. Function (PSCF)

GeoAI Models

Deep learning
(CNN + LSTM)
Cluster trajectory
Smoke plume prediction

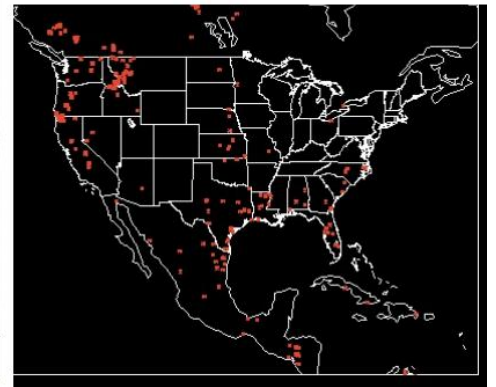
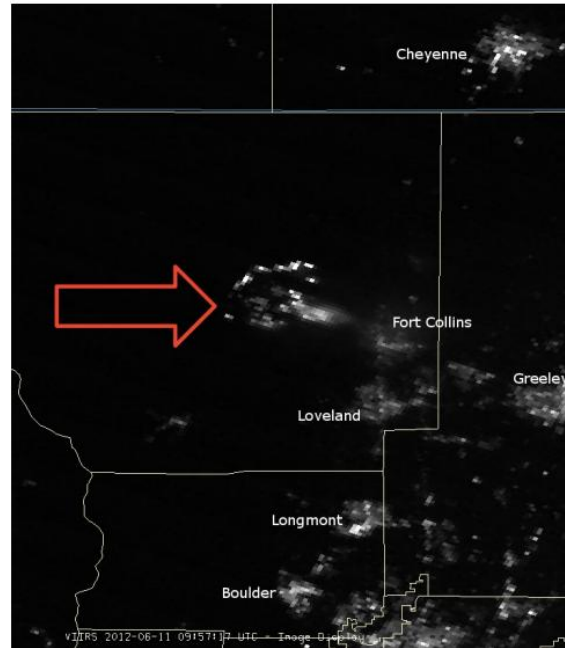
Methodology: GeoAI-Integrated Analysis Framework



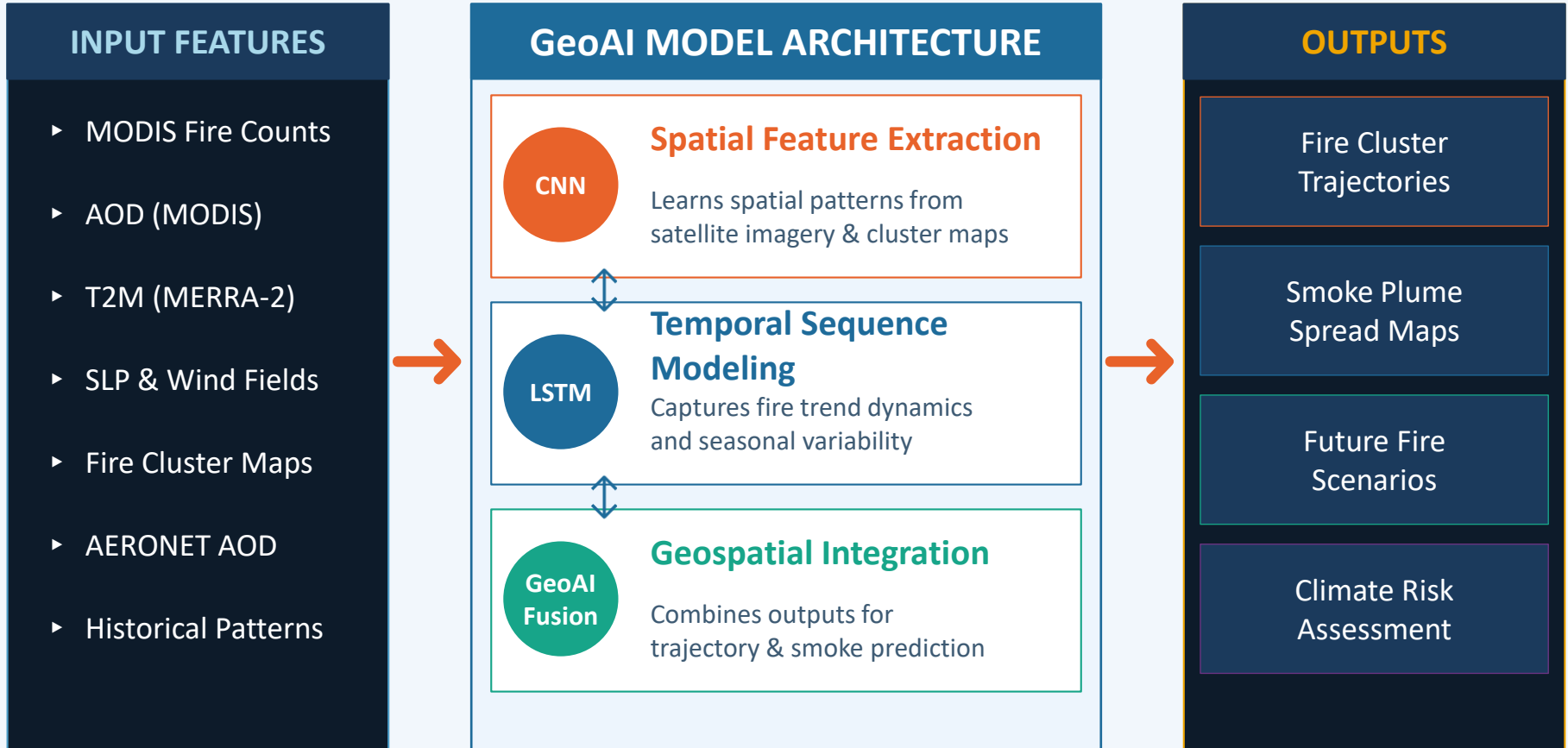
GeoAI Integration: Multi-source satellite remote sensing + Deep learning for comprehensive wildfire-smoke-climate dynamics

Methodology: GeoAI-Integrated Analysis Framework

- Light (Color)
- Heat (Temperature)
- Smoke (Contrast)



GeoAI Predictive Framework: Architecture & Outputs



Wildfire Cluster Dynamics: Spatial-Temporal Patterns

Fire Cluster Distribution — Northern Hemisphere (2000–2024)



2000–2017 (Baseline)

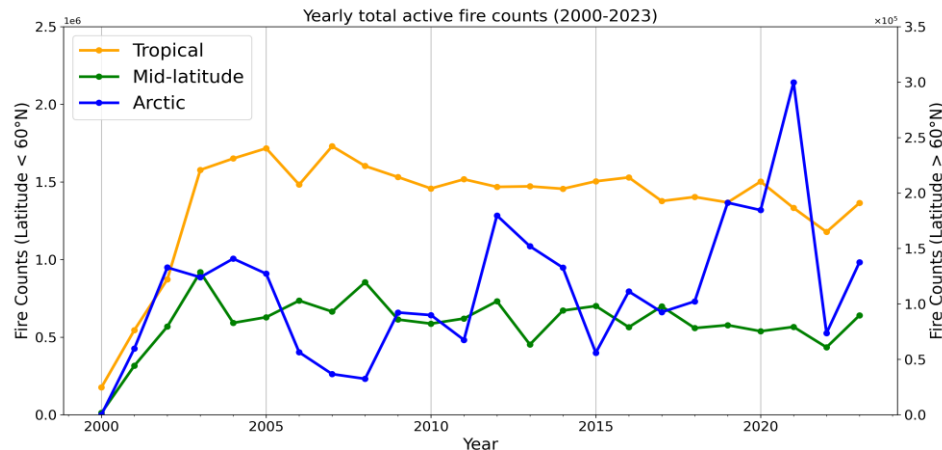
- Stable cluster patterns in boreal forests.
- Fire counts dominated by tropical/mid-latitude regions.
- Arctic fires rare and localized.

2018–2021 (Anomalous)

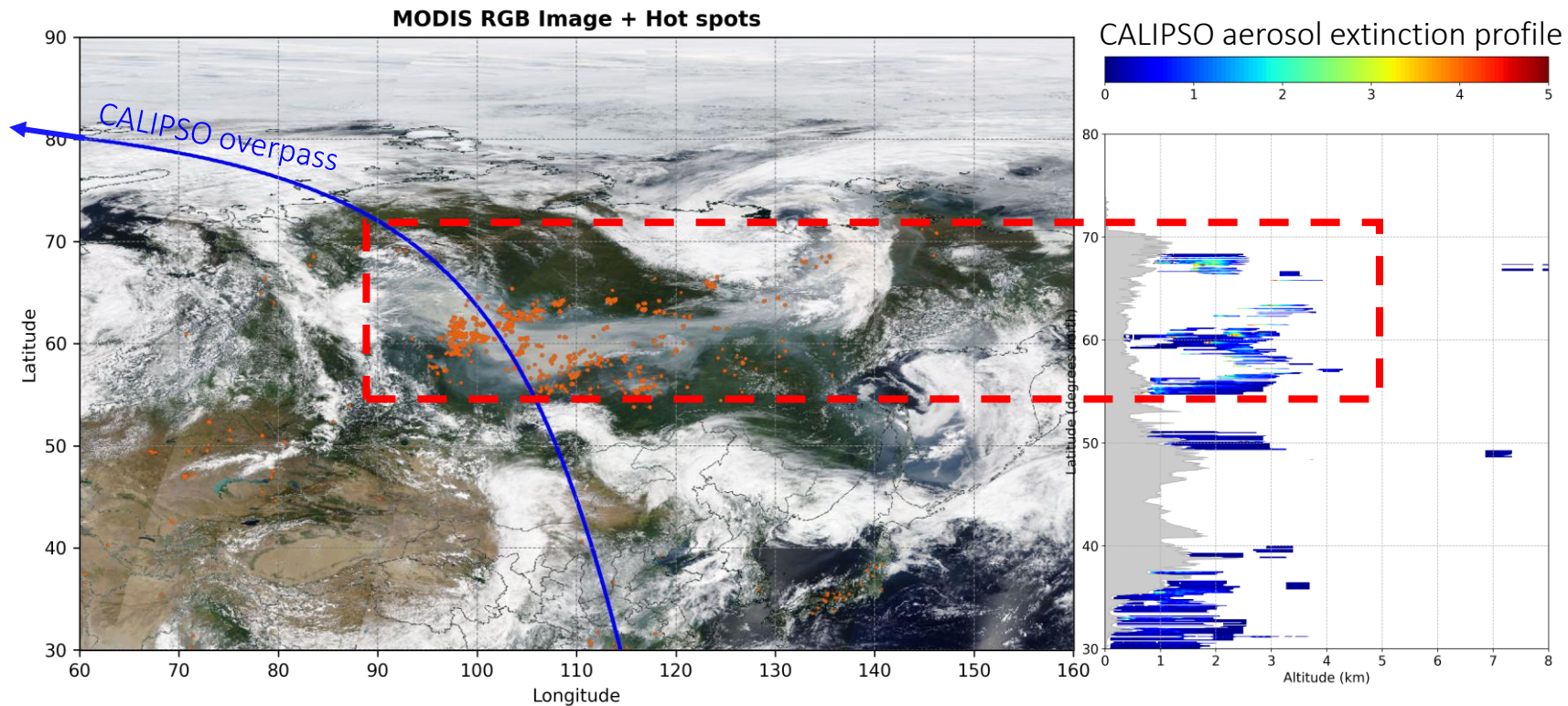
- Dramatic poleward cluster expansion.
- Record 299,863 Arctic fires in 2021; 191,262 in 2019.
- Cluster size and FRP markedly elevated in Siberia & Canada.

2022–2024 (Continued)

- Sustained intensification trend.
- GeoAI models detect accelerating cluster formation linked to climate-driven warming and drying conditions.

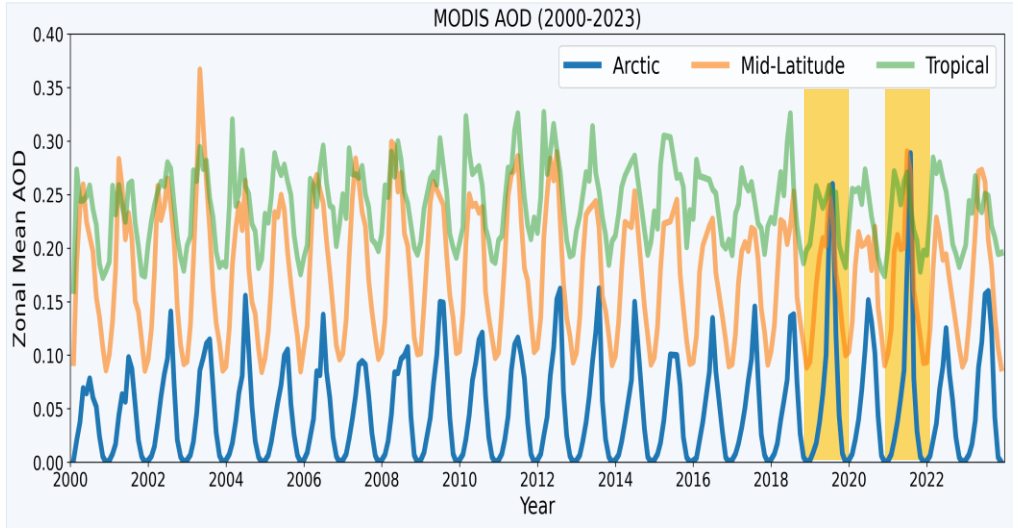


Satellite view of Fires & Smokes



Aerosol Optical Depth & Wildfire Smoke Transport

MODIS AOD — Zonal Mean Trend (2000–2023)



● Arctic (60–90°N) ● Mid-Latitude (30–60°N) ● Tropical (0–30°N)

⚠ Arctic AOD anomaly peak: Aug 2019 (0.260) & Aug 2021 (0.288) — exceeds mid-latitude & tropical values

Long-term Decline (2000–2018)

- Overall Arctic AOD decrease consistent with EU/NA emission regulations.
- General downward trend across most AERONET stations.

2018–2021 Anomalous Surge

- Yakutsk max AOD: 1.373 (5× avg).
- Bonanza Creek: 0.960 (5× avg).
- AOD ratio 3.7–5.8× historical mean — significant aerosol events.

Smoke Transport Pathways

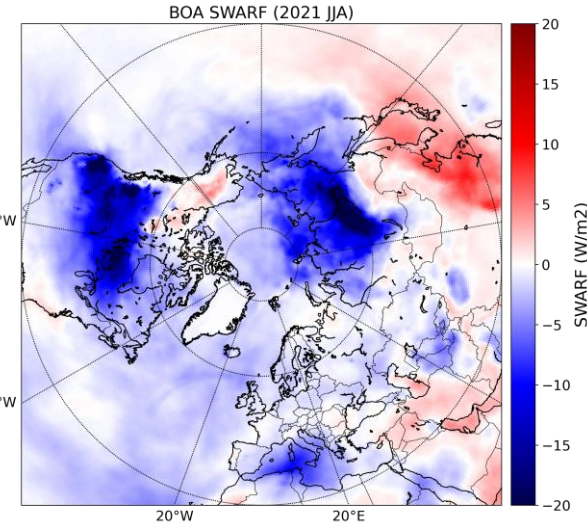
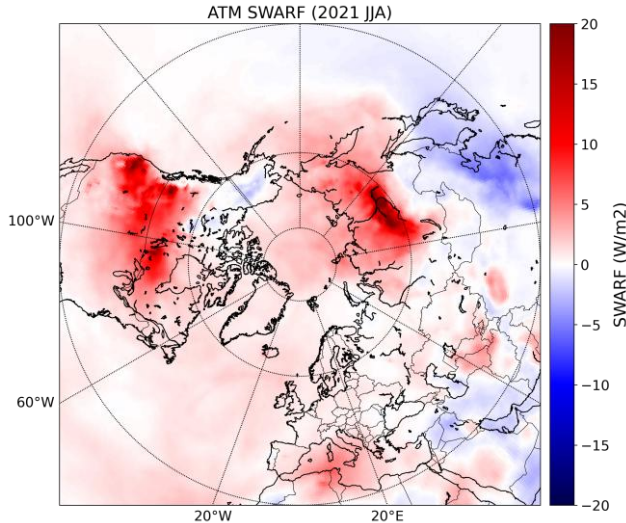
- HYSPLIT PSCF shows post-2018 air parcels arriving at Arctic stations originate from much larger northern source regions.
- CALIPSO: plume altitude 4–6 km.

Mechanism of Radiative Forcing



FEEDBACK: Carbonaceous aerosols absorb solar radiation → atmospheric warming → reinforces wildfire conditions → further aerosol emission

FE-Arctic ATM
8.38 W/m²
Baseline: 4.47



FE-Arctic BOA
-14.4 W/m²
Baseline: -7.76

Key Findings

01

Wildfire Cluster Intensification

- Arctic fire count: +5.08%/yr (2000–2024)
- Peak: 299,863 fires in 2021; 191,262 in 2019
- Clusters expanding poleward in N. America & Siberia
- Fire seasons lengthening under warming climate

02

Unprecedented AOD Anomalies

- Arctic AOD peaked at 5× historical average since 2018
- Yakutsk max AOD: 1.373 (Jul 2021)
- Bonanza Creek max AOD: 0.960 (Jun 2022)
- PSCF: post-2018 aerosol source regions shifted northward

03

Climate–Fire–Aerosol Feedback

- Summer T2M anomaly: +5K in 2019 & 2021 (Siberia/Sakha)
- SWARF ATM in FE_Arctic: +8.6 W/m² (2021)
- BOA surface cooling: deepened to −15.0 W/m² (2021)
- Carbonaceous aerosols amplify Arctic warming feedback loop

04

GeoAI Predictive Capability

- Deep learning captures spatio-temporal cluster dynamics
- Integrates MODIS, AERONET, CALIPSO & MERRA-2 inputs
- Predicts smoke plume spread under climate scenarios
- Enhances wildfire-smoke risk management frameworks

Conclusions & Future Directions

- 1 Wildfire clusters in the Northern Hemisphere are intensifying in frequency, spatial extent, and northward range under accelerating climate change
- 2 Arctic aerosol anomalies in 2019 & 2021 are directly coupled with record wildfire activity and enhanced long-range smoke transport
- 3 GeoAI-driven deep learning provides improved capabilities for predicting wildfire cluster trajectories and smoke plume dynamics
- 4 Enhanced aerosol radiative forcing creates climate-fire feedback loops, driving Arctic warming and further wildfire intensification

Future Directions

- Expand to Southern Hemisphere fire systems
- Real-time satellite feed integration into GeoAI pipeline
- Socioeconomic vulnerability mapping for wildfire risk
- Quantify wildfire emission budgets for climate models
- Develop operational early warning systems

Q & A

Thank You for Your Attention

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