Regional Radiative Effects of Wildfire Smoke

Analyses from the CERES Record

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NSF/UCAR/NCAR/ACOM/M Section (AMA/RSES Sub)

NASA/SMD/ESD/LaRC-E302/CERES/SARB Group

Outline

- Introduction
- Pacific Northwest
- Eastern Canada
- Eastern Australia
- Eastern Siberia
- Cross-Regional Synthesis
- Conclusions
- Supplemental Material
  - CERES EBAF + MODIS/VIIRS AOD + MERRA-2
  - Methods and Tables

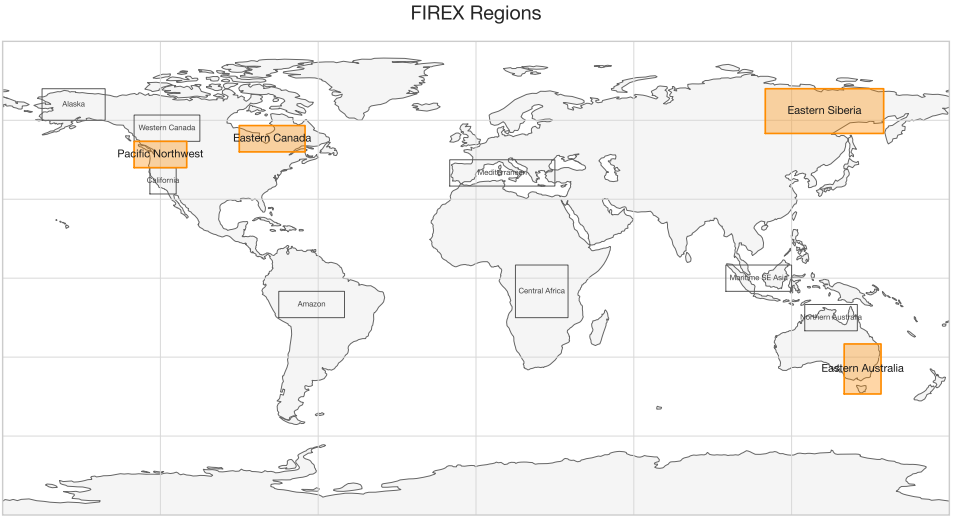
https://github.com/davidfillmore/FIREX

Fire Regional Emissions Explorer

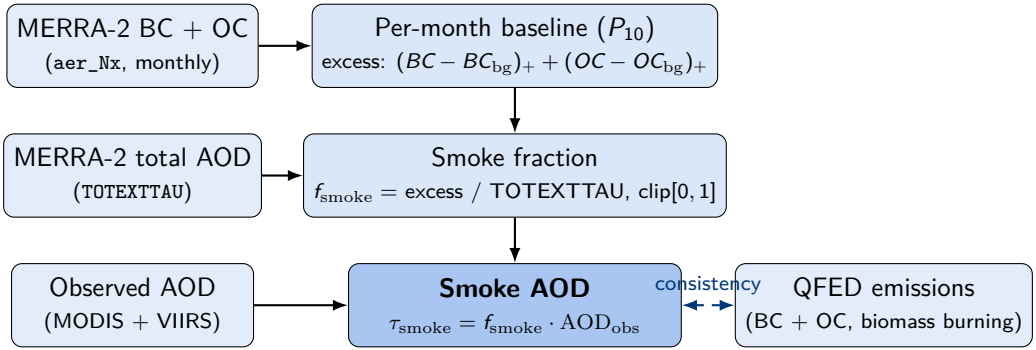
https://github.com/NCAR/DAVINCI

Data Analysis and Visual Intelligence for Climate

Study Regions

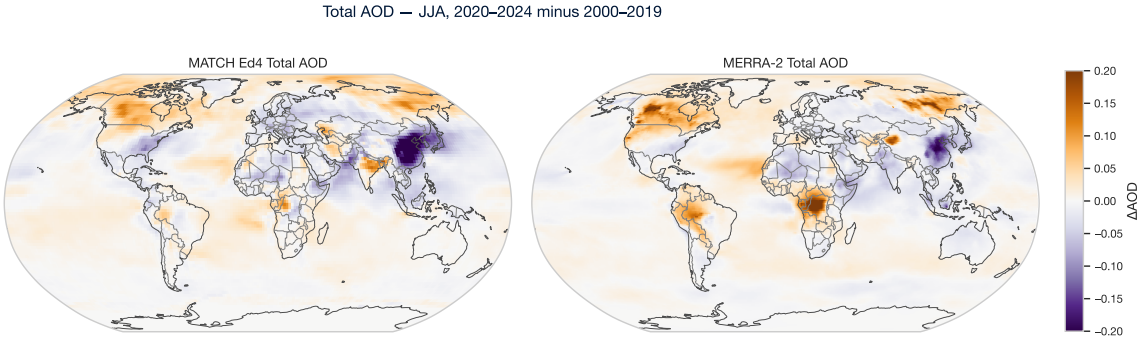


Smoke AOD Estimation



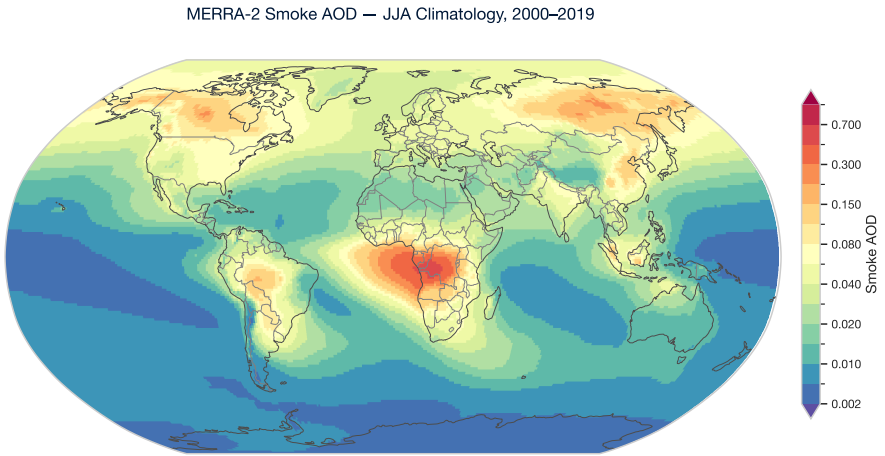
MERRA-2 species split sets the smoke fraction; observed AOD sets the magnitude; QFED emissions are an independent consistency check.

Total AOD Anomaly — MATCH Ed4 vs MERRA-2



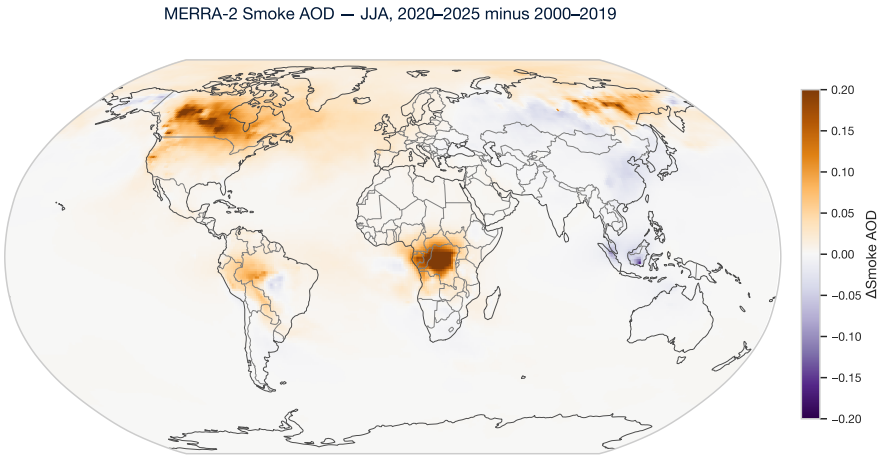
JJA total-AOD anomaly (2020–2024 vs 2000–2019), MATCH Ed4 (Model for Atmospheric Transport and Chemistry) vs MERRA-2 reanalysis.

Smoke AOD — JJA Climatology (2000–2019)



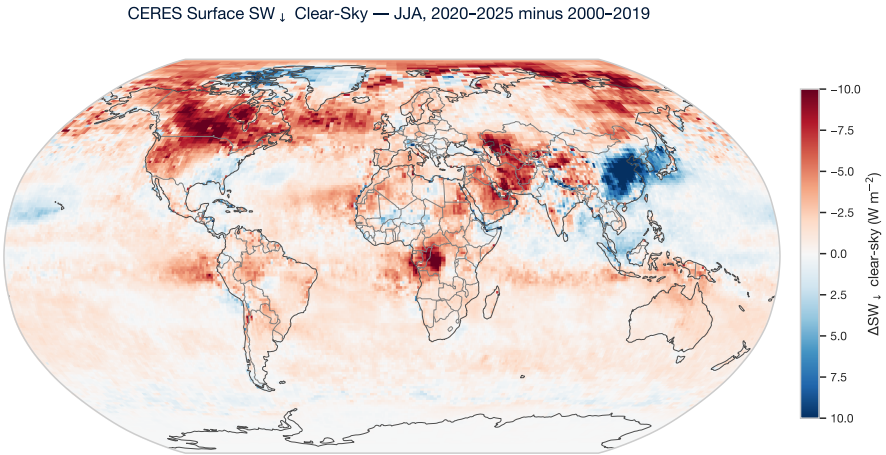
JJA smoke AOD (MERRA-2), 2000–2019 climatological mean.

Smoke AOD — Recent JJA Anomaly (2020–2025)



JJA smoke AOD (MERRA-2) anomaly, 2020–2025 vs 2000–2019.

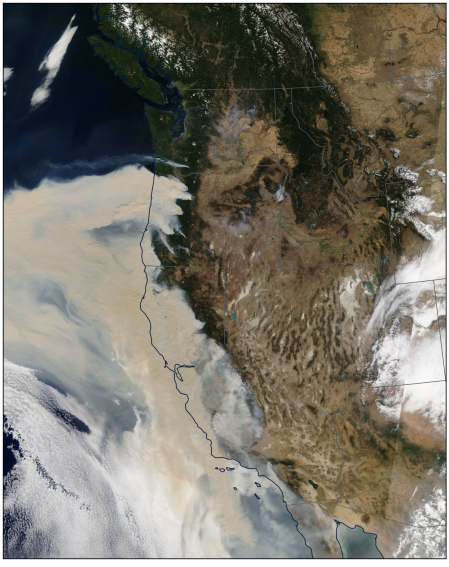
Surface SW (Clear-sky) — Recent JJA Anomaly



CERES EBAF clear-sky surface SW anomaly, 2020–2025 JJA vs 2000–2019.

Pacific Northwest

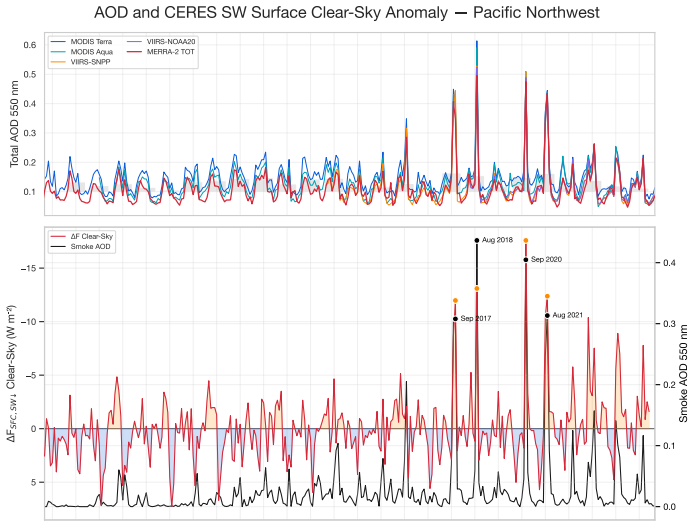
Recurring high-smoke fire seasons in a maritime-temperate biome.



MODIS true color, 9 September 2020. NASA Worldview.

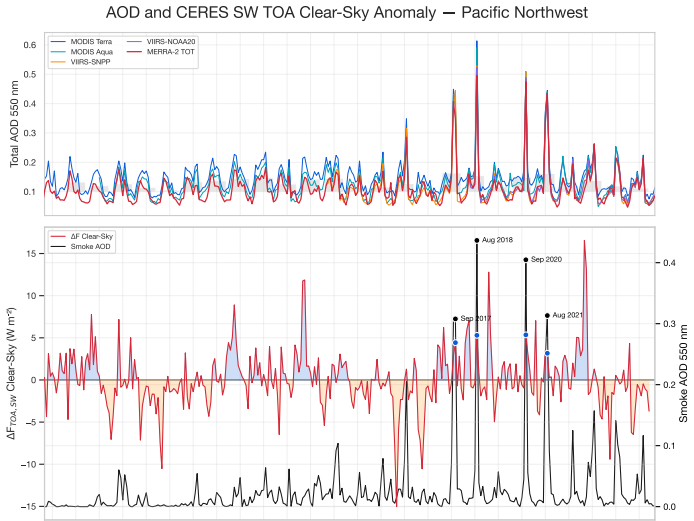
Pacific Northwest

Top: total column AOD (per-platform). Bottom: clear-sky CERES surface SW anomaly with ensemble-mean smoke AOD on the twin axis. Smoke months show paired AOD spikes and surface-SW depressions.



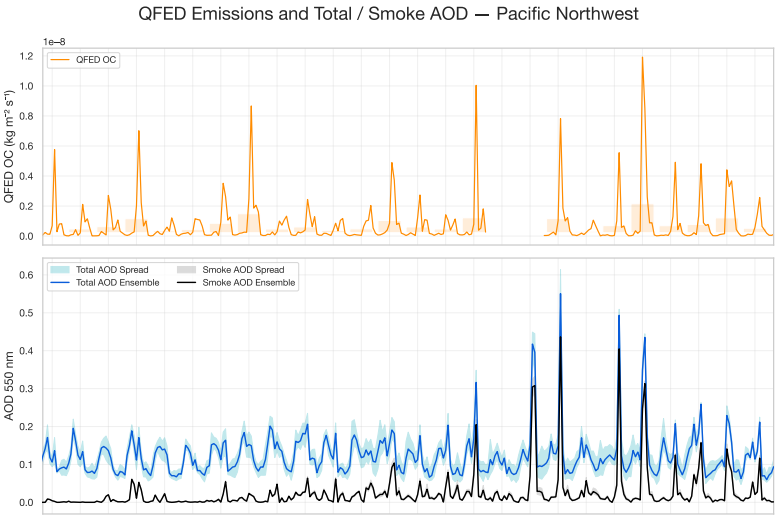
Pacific Northwest

Same construction at TOA. Outgoing SW anomalies track smoke months: positive excursions — more reflected SW — align with the peak τ_{smoke} years.

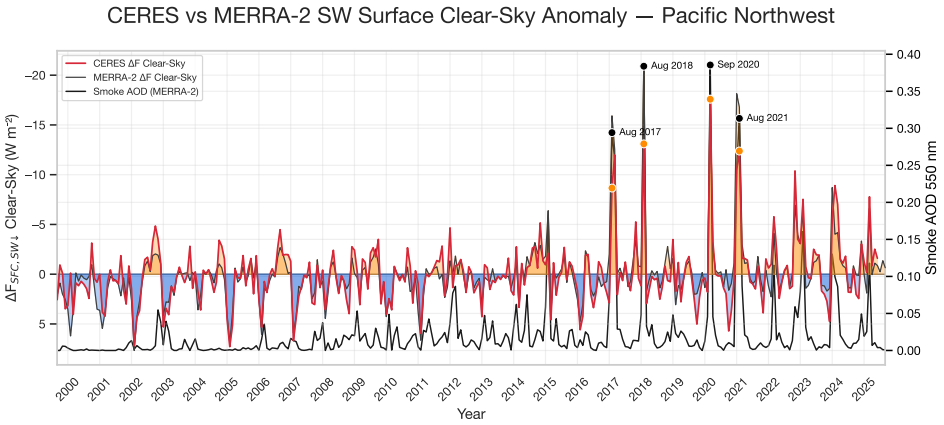


Pacific Northwest

QFED-derived smoke AOD: the biomass-burning AOD signal carried into MERRA-2 transport. Peaks align with the same smoke months that drive the observed clear-sky SW anomalies.

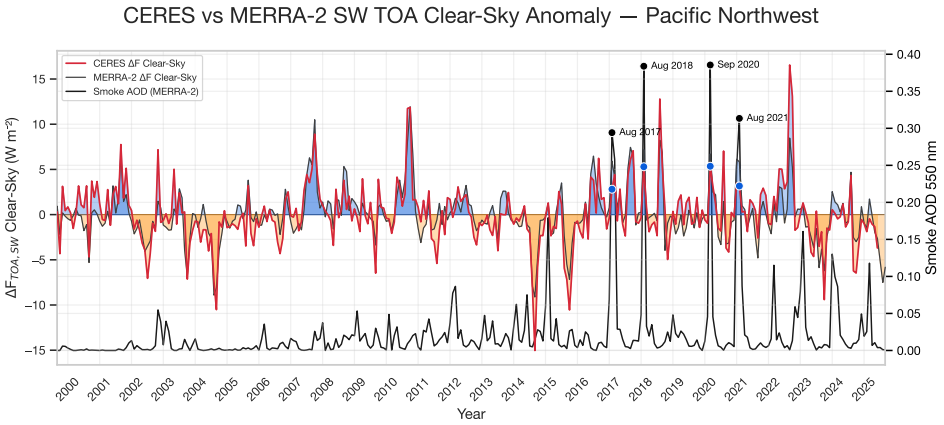


Pacific Northwest



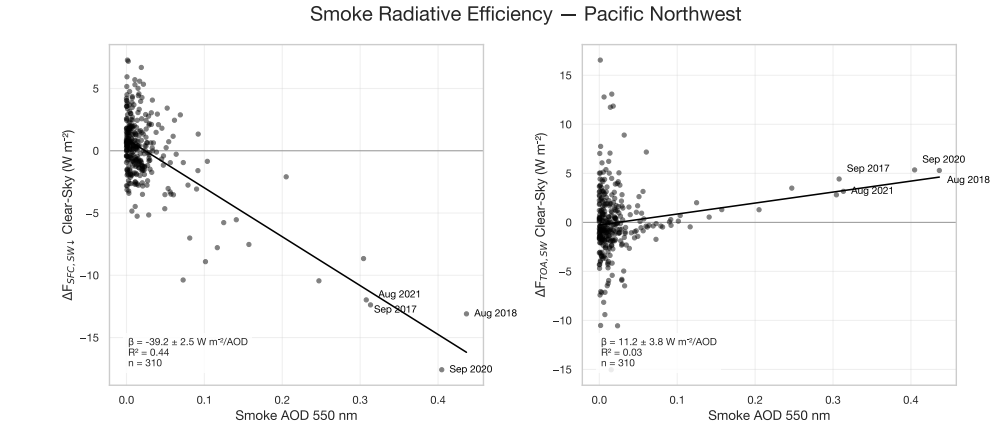
Clear-sky surface SW anomaly: CERES observed vs MERRA-2 model, with MERRA-2-internal smoke AOD on the twin axis. MERRA-2 generally over-deepens the surface dimming during peak-smoke months.

Pacific Northwest



Clear-sky TOA SW anomaly: CERES vs MERRA-2 overlay. Both show positive excursions during peak-smoke months; MERRA-2 amplifies the TOA response relative to CERES.

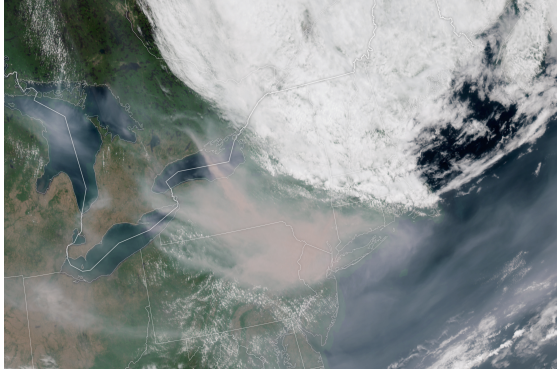
Pacific Northwest



Peak $\tau_{\mathrm{smoke}} = 0.44$ in 2018; CERES $\eta_{\mathrm{SFC}} = -39.2 \pm 2.5$ and $\eta_{\mathrm{TOA}} = +11.2 \pm 3.8\,\mathrm{W\,m^{-2}/AOD}$. Recurring 2017–2021 smoke months drive a clear surface-dimming signal.

Eastern Canada

The 2023 Quebec record season and its continental smoke plume.

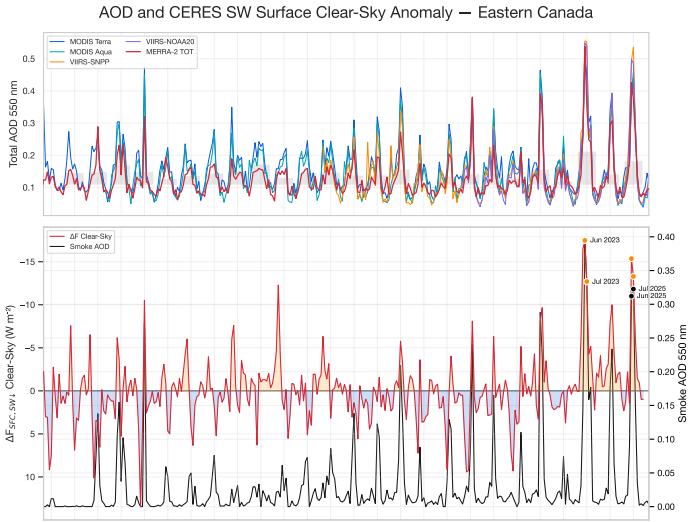


GOES-16 true color, 7 June 2023.

NASA Earth Observatory.

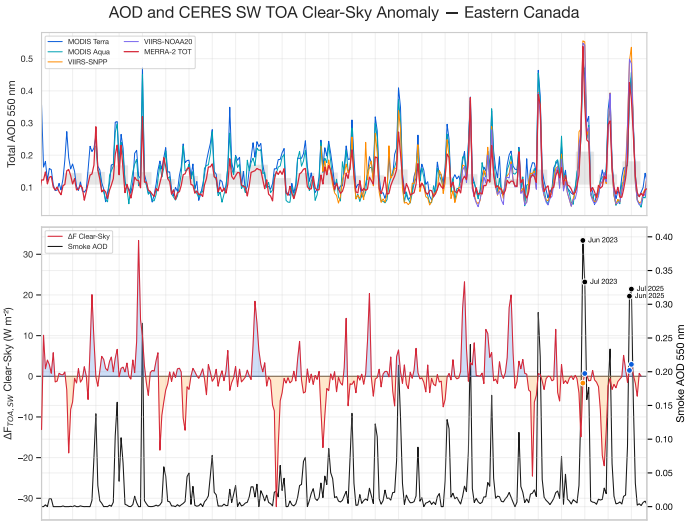
Eastern Canada

Top: total column AOD (per-platform). Bottom: clear-sky CERES surface SW anomaly with ensemble-mean smoke AOD on the twin axis. Smoke months show paired AOD spikes and surface-SW depressions.



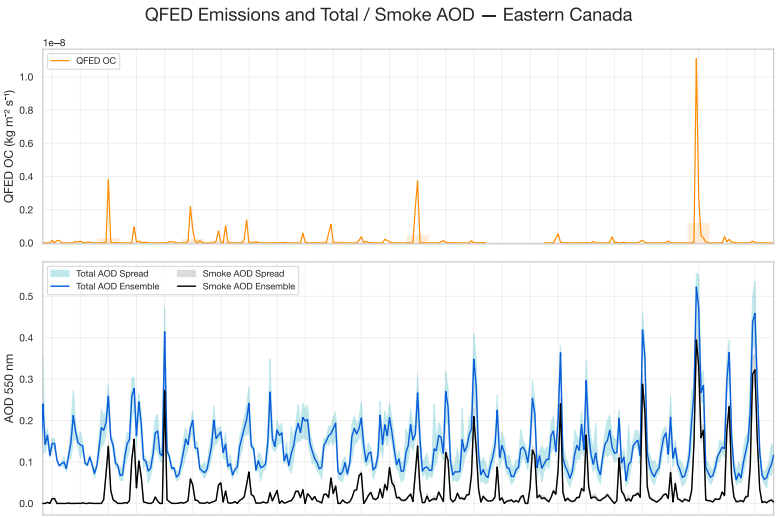
Eastern Canada

Same construction at TOA. Outgoing SW anomalies track smoke months: positive excursions — more reflected SW — align with the peak τ_{smoke} years.

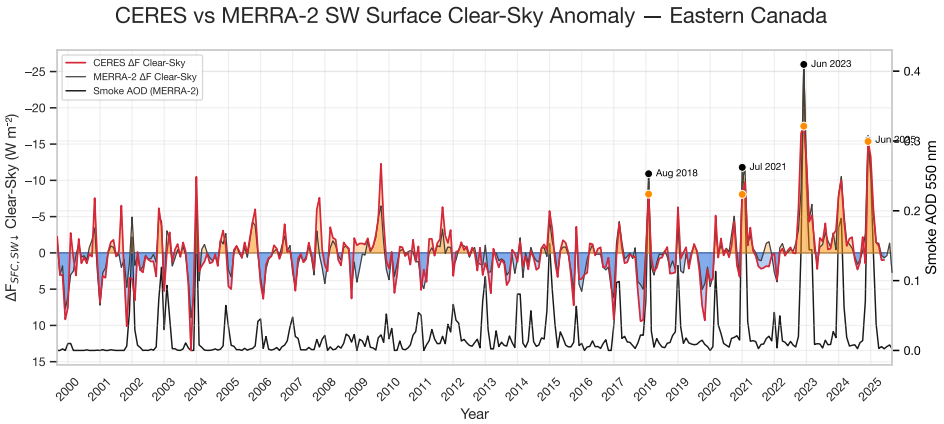


Eastern Canada

QFED-derived smoke AOD: the biomass-burning AOD signal carried into MERRA-2 transport. Peaks align with the same smoke months that drive the observed clear-sky SW anomalies.

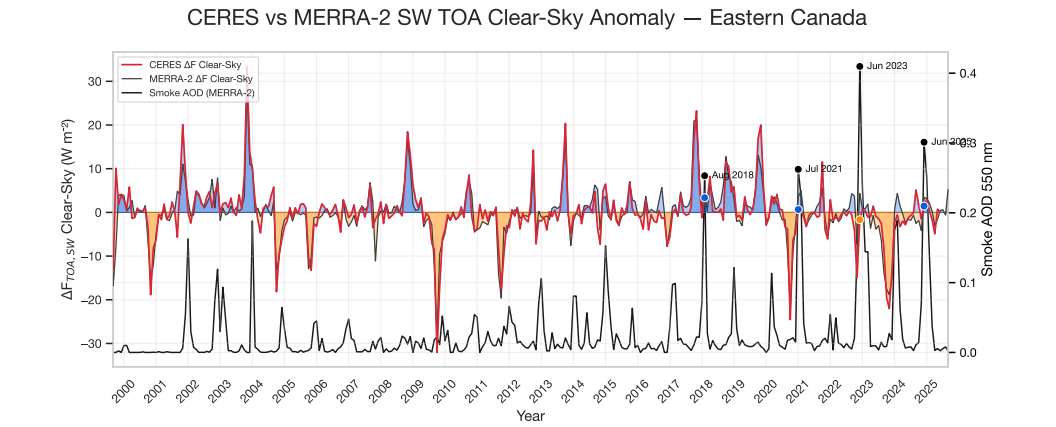


Eastern Canada



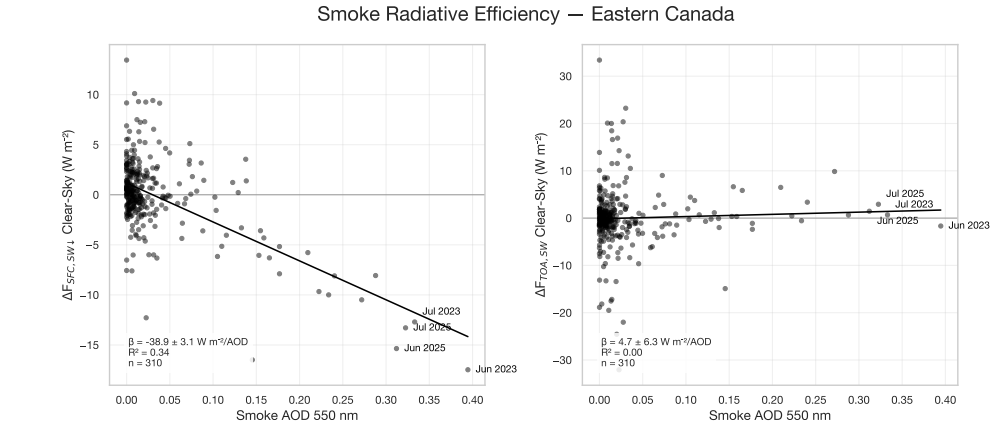
Clear-sky surface SW anomaly: CERES observed vs MERRA-2 model, with MERRA-2-internal smoke AOD on the twin axis. MERRA-2 modestly over-deepens the surface dimming during the 2023 peak.

Eastern Canada



Clear-sky TOA SW anomaly: CERES vs MERRA-2 overlay. MERRA-2 amplifies the TOA response relative to CERES, particularly during the 2023 peak.

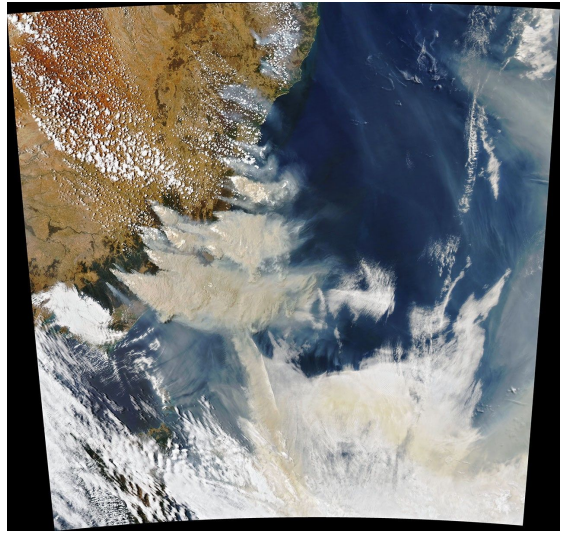
Eastern Canada



Peak $\tau_{\mathrm{smoke}} = 0.39$ in 2023; CERES $\eta_{\mathrm{SFC}} = -38.9 \pm 3.1$ and $\eta_{\mathrm{TOA}} = +4.7 \pm 6.3\,\mathrm{W\,m^{-2}/AOD}$. The surface signal is robust; the TOA point estimate is positive but weak relative to its uncertainty.

Eastern Australia

Black Summer 2019–20 and a stronger TOA response.

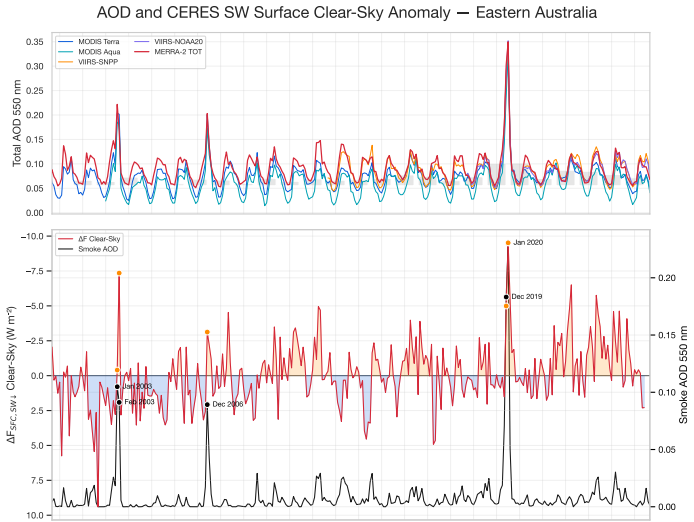


MODIS/Aqua true color, 4 January 2020.

NASA Earth Observatory.

Eastern Australia

Top: total column AOD (per-platform). Bottom: clear-sky CERES surface SW anomaly with ensemble-mean smoke AOD on the twin axis. Smoke months show paired AOD spikes and surface-SW depressions.



Eastern Australia

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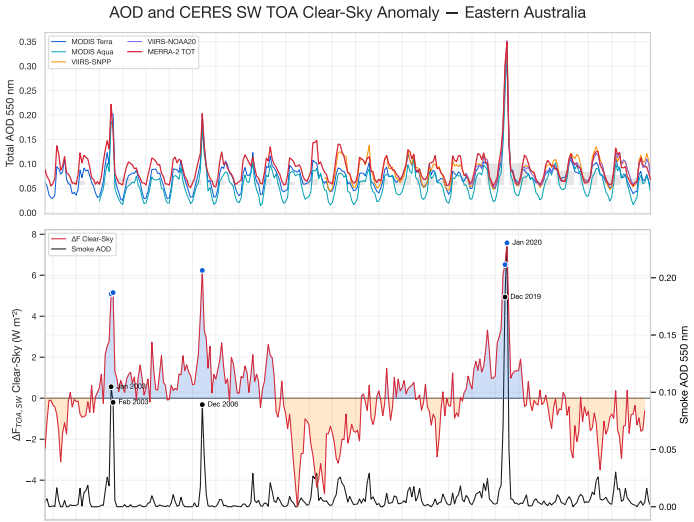
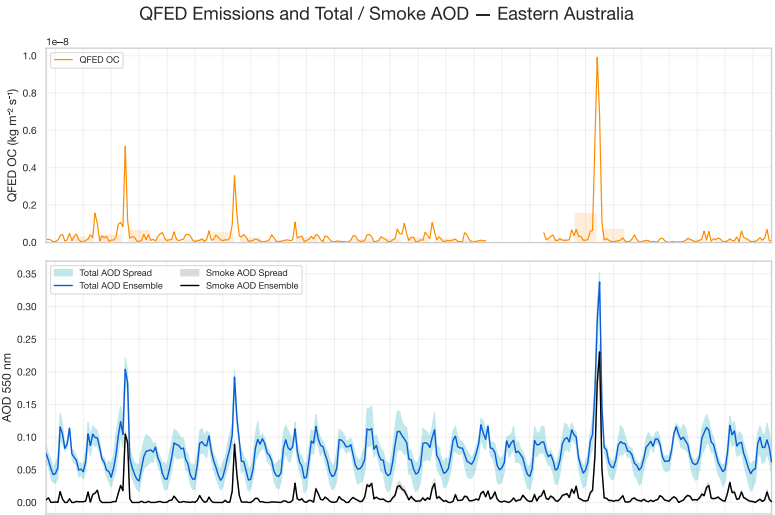
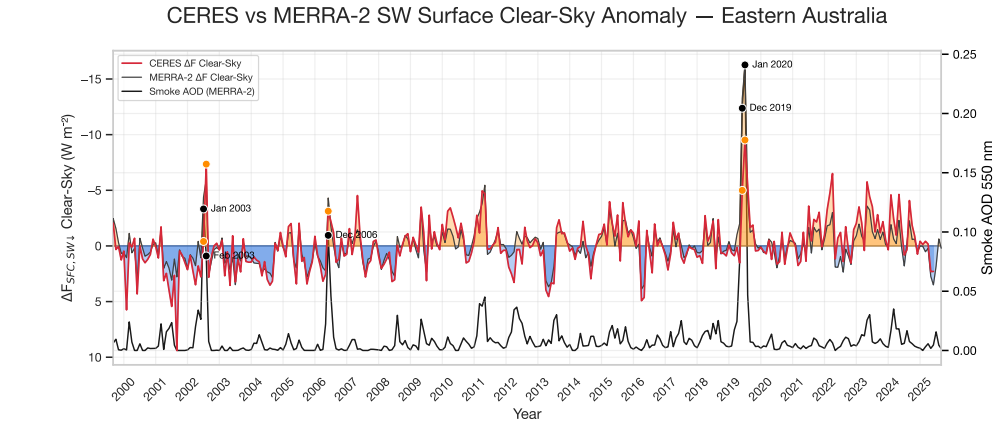


Eastern Australia

QFED-derived smoke AOD: the biomass-burning AOD signal carried into MERRA-2 transport. Peaks align with the same smoke months that drive the observed clear-sky SW anomalies.

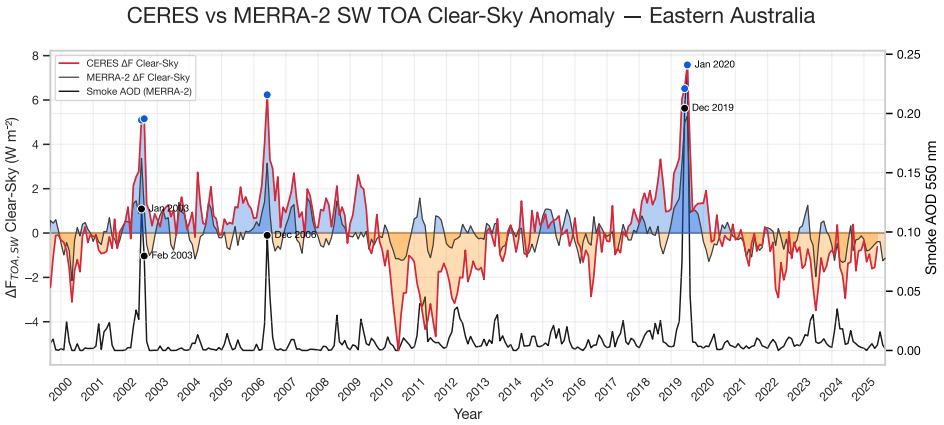


Eastern Australia



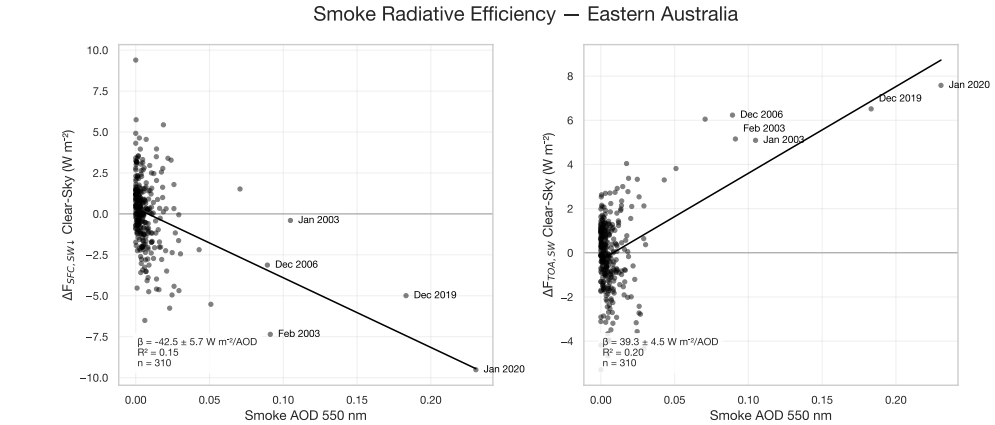
Clear-sky surface SW anomaly: CERES observed vs MERRA-2 model, with MERRA-2-internal smoke AOD on the twin axis. MERRA-2 substantially over-deepens the surface dimming during Black Summer.

Eastern Australia



Clear-sky TOA SW anomaly: CERES vs MERRA-2 overlay. Black Summer drives strong positive excursions in both; CERES is larger here — an inversion of the over-amplification pattern seen in the other featured regions.

Eastern Australia



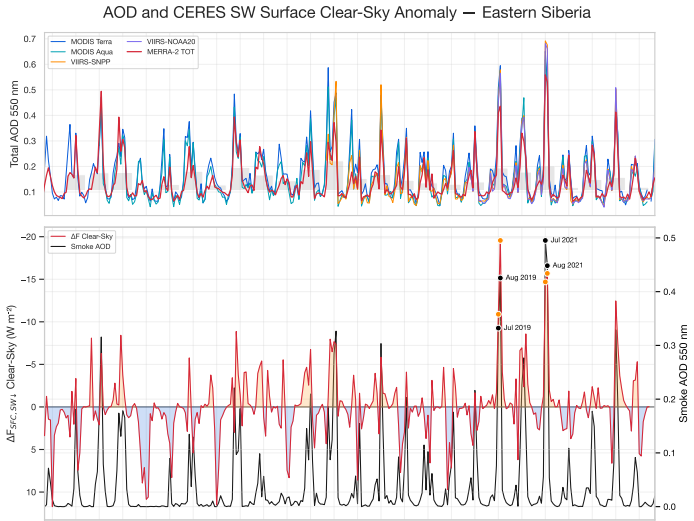
Peak $\tau_{\mathrm{smoke}} = 0.23$ in 2020; CERES $\eta_{\mathrm{SFC}} = -42.5 \pm 5.7$ and $\eta_{\mathrm{TOA}} = +39.3 \pm 4.5\,\mathrm{W\,m^{-2}/AOD}$. Black Summer produces the strongest featured-region TOA cooling response.

Eastern Siberia

The 2019 and 2021 Yakutia megafires in a boreal fire regime.

Eastern Siberia

Top: total column AOD (per-platform). Bottom: clear-sky CERES surface SW anomaly with ensemble-mean smoke AOD on the twin axis. Smoke months show paired AOD spikes and surface-SW depressions.



Eastern Siberia

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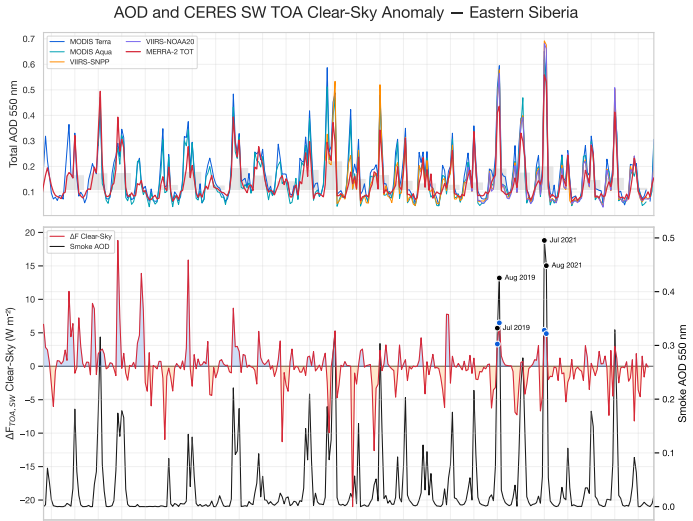
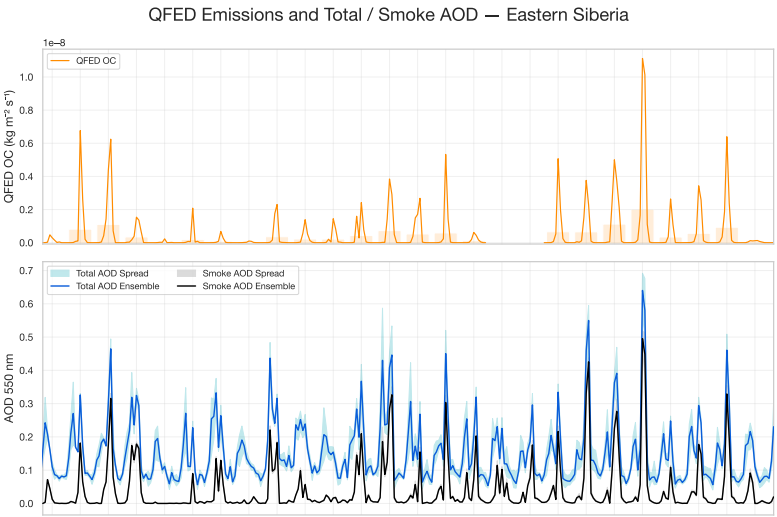
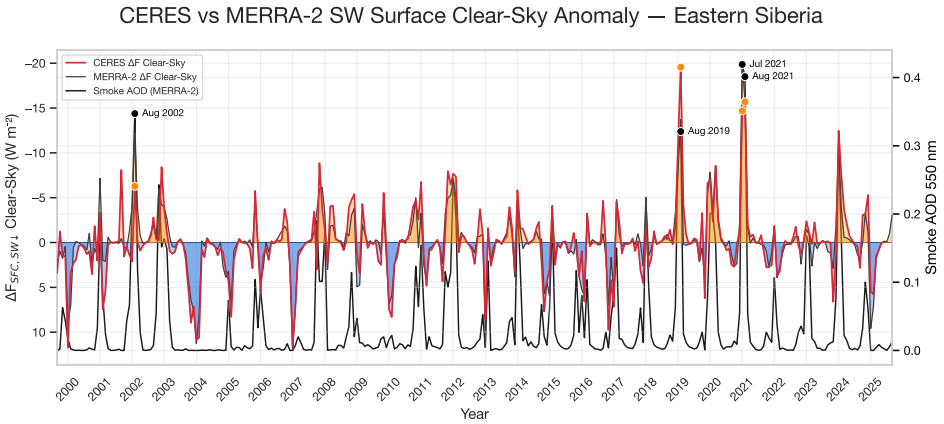


Eastern Siberia

QFED-derived smoke AOD: the biomass-burning AOD signal carried into MERRA-2 transport. Peaks align with the same smoke months that drive the observed clear-sky SW anomalies.

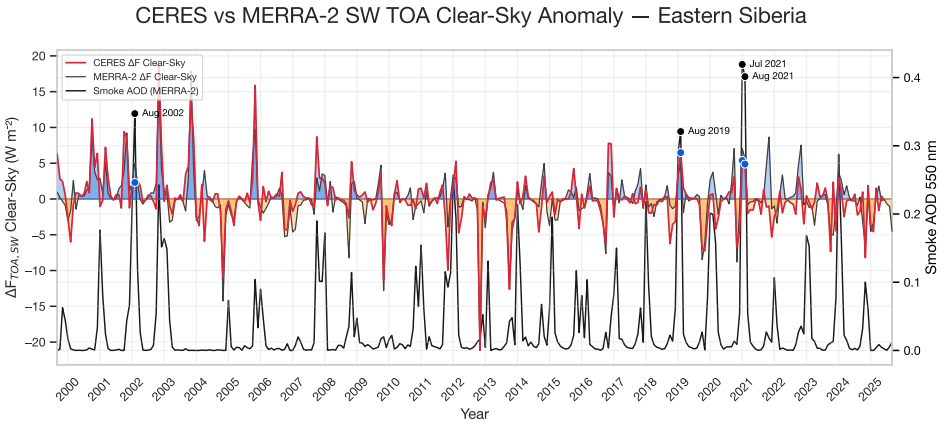


Eastern Siberia



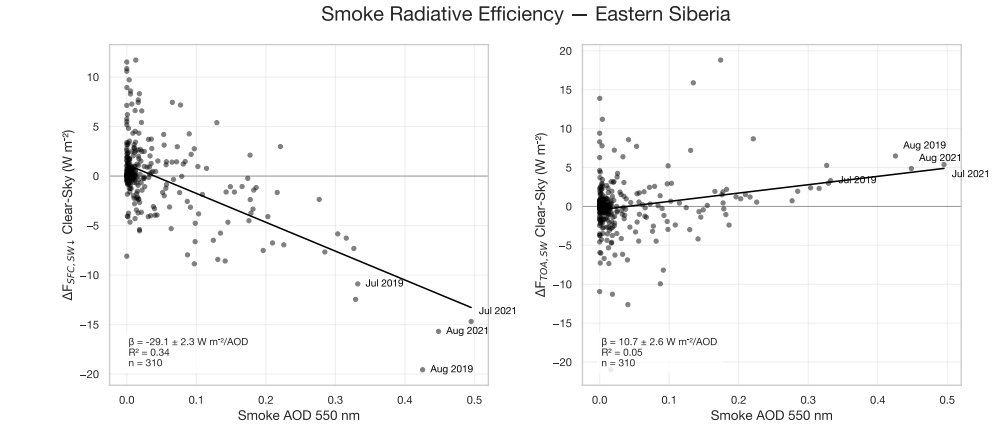
Clear-sky surface SW anomaly: CERES observed vs MERRA-2 model, with MERRA-2-internal smoke AOD on the twin axis. MERRA-2 closely tracks CERES at the surface — the closest model-observation agreement among the featured regions.

Eastern Siberia



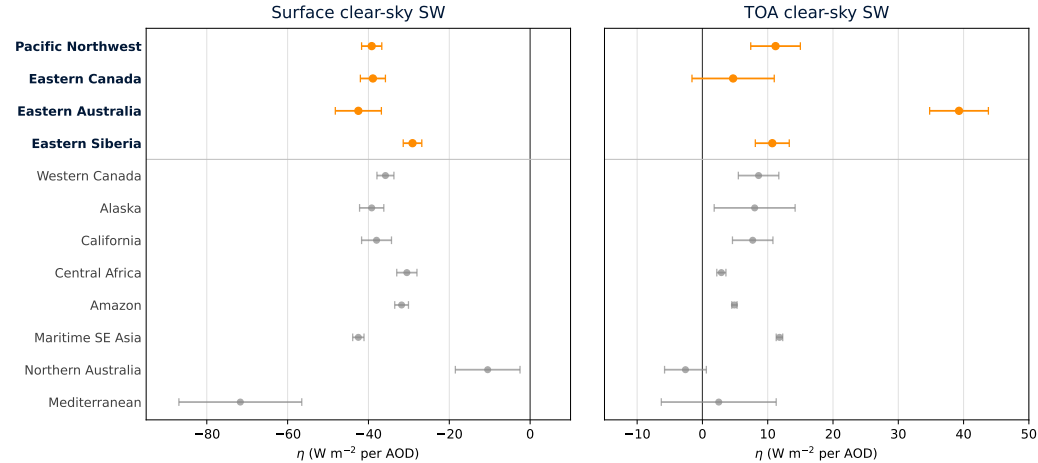
Clear-sky TOA SW anomaly: CERES vs MERRA-2 overlay. MERRA-2 closely tracks CERES at TOA, with the smallest model-observation gap among the featured regions.

Eastern Siberia

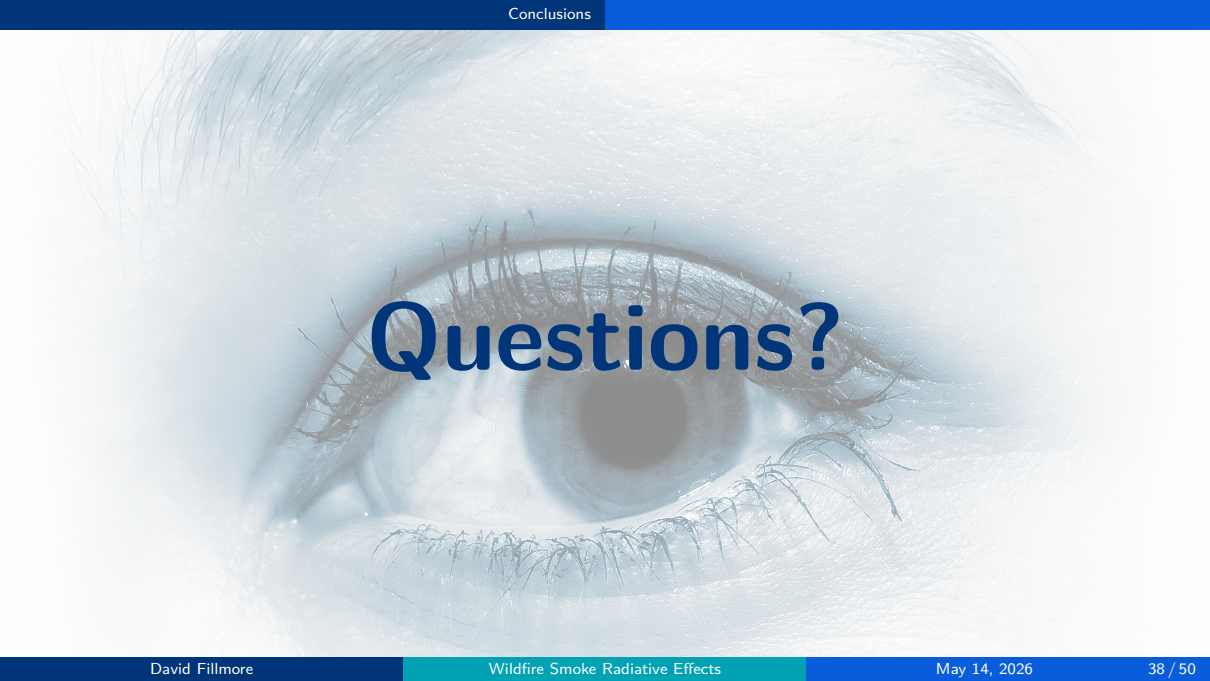


Peak $\tau_{\text{smoke}} = 0.50$ in 2021; CERES $\eta_{\text{SFC}} = -29.1 \pm 2.3$ and $\eta_{\text{TOA}} = +10.7 \pm 2.6\,\text{W m}^{-2}/\text{AOD}$. The surface slope is shallower than the other featured regions, but the high-smoke months still show clear dimming.

Regional Radiative-Efficiency Summary



Error bars are 1σ OLS slope uncertainty. Featured regions cluster around -29 to $-43\,\mathrm{W\,m^{-2}/AOD}$ at the surface, while Eastern Australia has the largest positive TOA slope.


Questions?

Supplemental Material

Methods, datasets, and attribution detail.

Methods

Estimating the smoke component of total AOD.

Datasets

Role	Dataset (version, period)	Native resolution
Radiative response	CERES EBAF Ed4.2.1 (2000-03 $\rightarrow$ 2025-12)	1° monthly
Total column AOD	MODIS Terra/Aqua MOD08/MYD08_M3 C6.1 (2000-02 $\rightarrow$)	1° monthly L3
Total column AOD	VIIRS AERDB M3 SNPP+NOAA-20 (2012-03 $\rightarrow$)	1° monthly L3
Speciated AOD	MERRA-2 `aer_Nx` monthly (2000-01 $\rightarrow$)	$0.5° \times 0.625°$ monthly
BB emissions	QFED v2.6r1 (2000 $\rightarrow$)	$0.25° \times 0.3125°$ daily

Radiation and Column AOD

- **CERES EBAF Ed4.2.1.** Radiative response. TOA and SFC SW + LW + net at monthly 1°, 2000-03 → 2025-12 in a single global granule. Provides the dependent variable: anomalies in TOA / SFC radiation that we regress on smoke-AOD.
- **MODIS Terra/Aqua + VIIRS SNPP/NOAA-20.** Observed total column AOD. Four platforms at monthly 1° L3; the platform overlap supplies cross-sensor consistency and continuity from MODIS-Terra (2000-02 →) through the VIIRS era. This is the AOD field we attribute smoke fraction *into*.
- **MERRA-2 `aer_Nx`.** Speciated AOD: BC, OC, sulfate, dust, sea salt, monthly $0.5° \times 0.625°$. Used for an internally consistent species *split*, not as the absolute AOD constraint — MERRA-2 ingests QFED as its biomass-burning source, while the final smoke-AOD magnitude is anchored to observed MODIS/VIIRS AOD.

Biomass-Burning Emissions

- **QFED v2.6r1.** Daily biomass-burning emissions on the MERRA-2 grid ($0.25° \times 0.3125°$), 7 species (BC, OC, $PM_{2.5}$, CO, SO_2, NO, NH_3) with biome breakdown. Aggregated to monthly for an emissions-to-AOD sanity check against the MERRA-2 species fractions. Known QFED 2016/2017 quality windows are masked in the plot workflow.

Smoke-AOD Attribution

Total observed AOD mixes smoke with dust, sulfate, sea salt, and background carbonaceous aerosol. We use MERRA-2 for an internally consistent *fractional* species split, while constraining magnitude with observed AOD. With no built-in biomass-burning split, smoke is estimated as the seasonal-baseline excess of BC + OC, then re-anchored in observed total AOD:

$$
\begin{aligned}
\mathrm{BC}_{\mathrm{bg}}(m) &= P_{10}\big(\mathrm{BCEXTTAU} \,\big|\, \text{cal. month } m\big) \\
\mathrm{OC}_{\mathrm{bg}}(m) &= P_{10}\big(\mathrm{OCEXTTAU} \,\big|\, \text{cal. month } m\big) \\
\tau^{\mathrm{M2}}_{\mathrm{smoke}}(t) &= \max\!\big(0,\ \mathrm{BCEXTTAU}(t) - \mathrm{BC}_{\mathrm{bg}}\big) + \max\!\big(0,\ \mathrm{OCEXTTAU}(t) - \mathrm{OC}_{\mathrm{bg}}\big) \\
f_{\mathrm{smoke}}(t) &= \mathrm{clip}\big[\tau^{\mathrm{M2}}_{\mathrm{smoke}}(t)/\mathrm{TOTEXTTAU}(t),\ 0,\ 1\big] \\
\tau^{\mathrm{obs}}_{\mathrm{smoke}}(t) &= f_{\mathrm{smoke}}(t) \cdot \mathrm{AOD}_{\mathrm{obs}}(t)
\end{aligned}
$$

The 10th percentile across ∼26 yr of monthly data is the ∼3rd-lowest year per calendar month — a robust proxy for the non-fire (anthropogenic + biogenic SOA) baseline.

Sanity Check: Emissions → AOD

Coarse box-model translation of QFED emissions to AOD — a dimensional check on the MERRA-2-anchored attribution:

$$\tau^{\mathrm{box}}_{\mathrm{smoke}} \approx E \cdot \tau_{\mathrm{res}} \cdot \mathrm{MEE} \cdot 10^3$$

- E — biomass-burning emission flux ($\mathrm{kg\,m^{-2}\,s^{-1}}$) from QFED
- τ_{res} — aerosol residence time ($\sim 7\,\mathrm{d}$ for fine-mode BB aerosol)
- MEE — mass extinction efficiency at 550 nm ($\sim$ 3–5 $\mathrm{m^2\,g^{-1}}$ for fresh BB)
- 10^3 — kg-to-g conversion for the MEE units

Ignores transport: under-predicts in receptor regions, over-predicts at the source. An order-of-magnitude check, not a quantitative retrieval.

Tables

Quantitative summaries of regional smoke radiative effects.

Regional Radiative Efficiency

Clear-sky CERES SW anomalies regressed on observed smoke AOD, monthly resolution, over the CERES record. Peak smoke and event-month count summarize the regional fire-season intensity:

Region	**Peak τ_{smoke} (yr)**	**$n \geq 50\%$ peak**	**η_{SFC} (W m^{-2}/AOD)**	**η_{TOA} (W m^{-2}/AOD)**
Pacific Northwest	0.44 (2018)	6	-39.2 ± 2.5	$+11.2 \pm 3.8$
Eastern Canada	0.39 (2023)	10	-38.9 ± 3.1	$+4.7 \pm 6.3$
Eastern Australia	0.23 (2020)	2	-42.5 ± 5.7	$+39.3 \pm 4.5$
Eastern Siberia	0.50 (2021)	10	-29.1 ± 2.3	$+10.7 \pm 2.6$

Sign convention: $-\eta_{\mathrm{SFC}}$ = surface dimming, $+\eta_{\mathrm{TOA}}$ = more outgoing SW = TOA cooling. All four featured regions show surface dimming; TOA point estimates are positive, with Eastern Canada weak relative to its uncertainty.

Other Regions

Same regression as the featured-regions table, run on the remaining regions defined in FIREX:

Region	**Peak τ_{smoke} (yr)**	**$n \geq 50\%$ peak**	**η_{SFC} (W m^{-2}/AOD)**	**η_{TOA} (W m^{-2}/AOD)**
Western Canada	0.73 (2023)	4	-35.8 ± 2.1	$+8.6 \pm 3.1$
Alaska	0.40 (2004)	7	-39.2 ± 3.0	$+8.0 \pm 6.2$
California	0.39 (2020)	3	-38.0 ± 3.7	$+7.7 \pm 3.1$
Central Africa	0.39 (2024)	6	-30.5 ± 2.5	$+2.9 \pm 0.7$
Amazon	1.36 (2024)	2	-31.8 ± 1.7	$+4.9 \pm 0.4$
Maritime SE Asia	1.10 (2015)	3	-42.5 ± 1.4	$+11.8 \pm 0.5$
Northern Australia	0.11 (2012)	18	-10.5 ± 8.0	-2.6 ± 3.2
Mediterranean	0.06 (2025)	6	-71.7 ± 15.2	$+2.5 \pm 8.8$

Surface dimming is visible across most regions. Northern Australia is weak relative to uncertainty (low peak τ, broad season); Mediterranean's slope is large but noisy at very low smoke loadings.

Regional Context

- The featured regions sit in the stable part of the regional screen: peak smoke AOD is large enough to fit a surface slope, and η_{SFC} falls in a narrow -29 to $-43\,\mathrm{W\,m^{-2}/AOD}$ range.
- Mediterranean and Northern Australia are the main surface outliers. Both have low peak smoke AOD and large slope uncertainties, so they are better treated as low-signal cases than as contradictory physics.
- TOA response is less uniform than surface dimming. Eastern Australia stands out with a large positive TOA slope, while Eastern Canada has a positive point estimate but broad uncertainty.

Interpretation. The robust first-order result is regional surface dimming by smoke. TOA cooling is present in the featured-region point estimates, but its magnitude is more sensitive to region, cloud state, surface albedo, and monthly aggregation.

Takeaways and Future Work

Takeaways

- Surface dimming consistent across all four featured biomes: $\eta_{\mathrm{SFC}} \approx -29$ to $-43\,\mathrm{W\,m^{-2}/AOD}$; TOA SW point estimates are positive, with Eastern Canada weak relative to uncertainty.
- Magnitudes broadly consistent with literature. Monthly-aggregation regression dampens β relative to per-event radiative efficiency (literature -50 to $-70\,\mathrm{W\,m^{-2}/AOD}$); the dampening is modest at plausible nonlinearity exponents.
- MERRA-2 model η_{SFC} values are generally more negative than CERES (e.g. Eastern Australia: -71.0 model vs -42.5 observed). Open methodological question — speciation accuracy, aging chemistry, or both.

Future work

- Daily-data path: CERES SYN1deg + daily MODIS L3 + daily MERRA-2 for per-event β. Single fire-active year per region as a scoped first pass.
- All-sky CERES + cloud-aerosol interaction; lagged-AOD effects; detrending vs month-of-year fixed effects.