



Long-Term Trends and ENSO–Aerosol Modulation of Surface Solar Radiation Over India

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Introduction & Motivation

Surface solar radiation (SSR) governs the Earth’s energy balance, atmospheric circulation, agricultural productivity, and solar-energy potential. Global SSR has passed through decades of “dimming” and partial “brightening,” driven by shifting aerosol loads and cloud cover. India’s rapid industrialisation, dense aerosol loading over the Indo-Gangetic Plain, and strong monsoon–ENSO coupling make it a critical test-bed for these radiative changes. This poster synthesizes two complementary IMD studies, a 54-year trend analysis and an ENSO / aerosol attribution study, into one unified picture of what is driving India’s changing solar climate.

Two Complementary Studies

STUDY A — Long-Term Trends

12 IMD stations · 1970–2023 (54 yrs)
Mann–Kendall test + Sen’s slope
ERA5 cloud-cover context (2001–2023)

STUDY B — ENSO & Aerosol Drivers

15 IMD stations · 2003–2023 (21 yrs)
Oceanic Niño Index correlation + composites
ERA5 cloud + Copernicus CAMS AOD₅₅₀

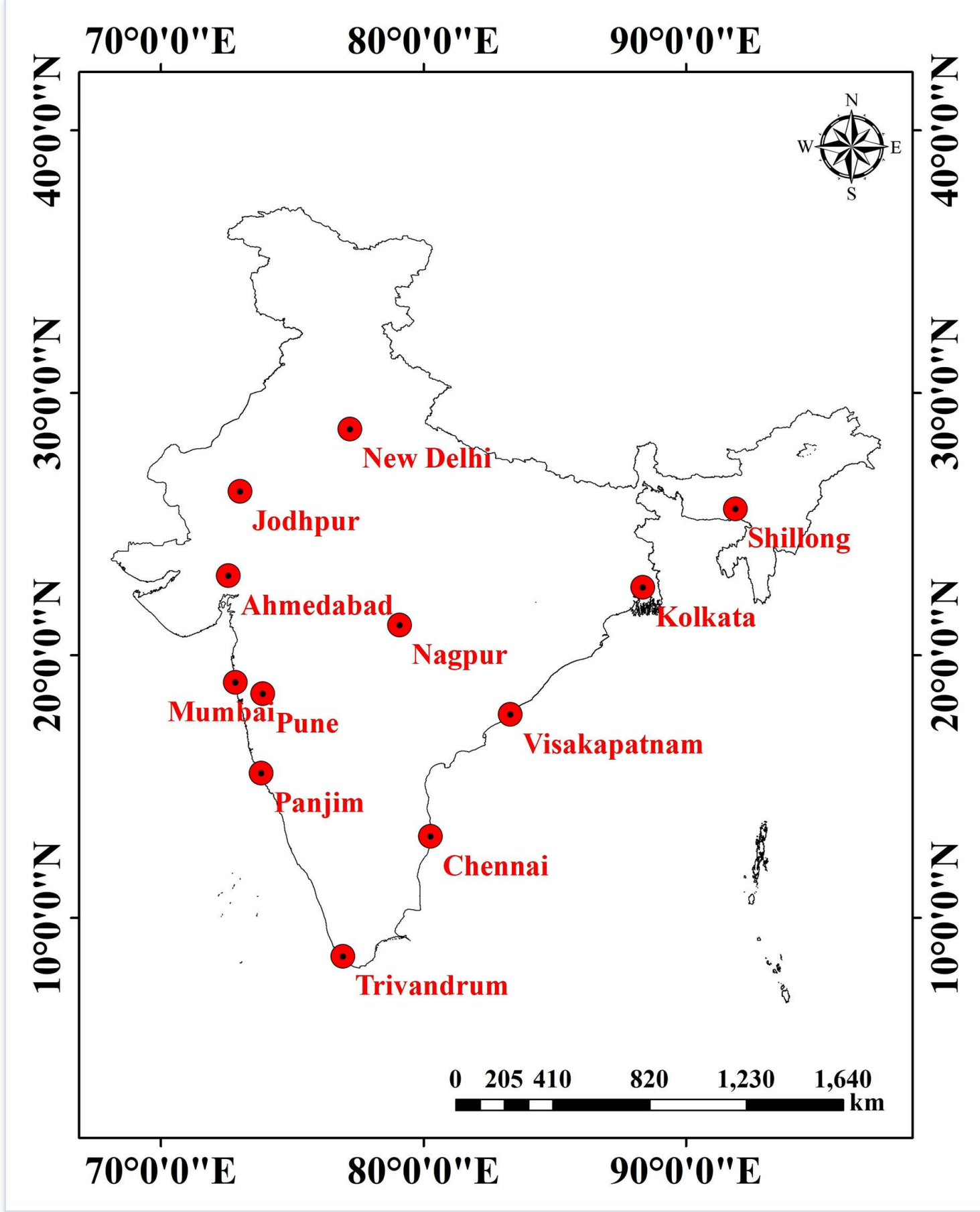


Figure 1. The 12-station IMD pyranometer network (Study A) spans arid, semi-arid, tropical, coastal and monsoon-highland climates across India — from Jodhpur’s hot desert to Shillong’s subtropical highlands.

Discussion: This climatic spread lets the study test whether the observed dimming is a nationwide signal or a local artefact, finding it at all 12 sites, regardless of climate, points to a shared underlying driver.

Study B extends this to 15 stations (adding Srinagar, Varanasi and Bhopal) spanning Koppen classes from cold, dry-summer continental (Dsb) and hot desert (BWh) to tropical monsoon (Am) and tropical savanna (Aw), capturing India’s full climatic gradient for ENSO/aerosol attribution.

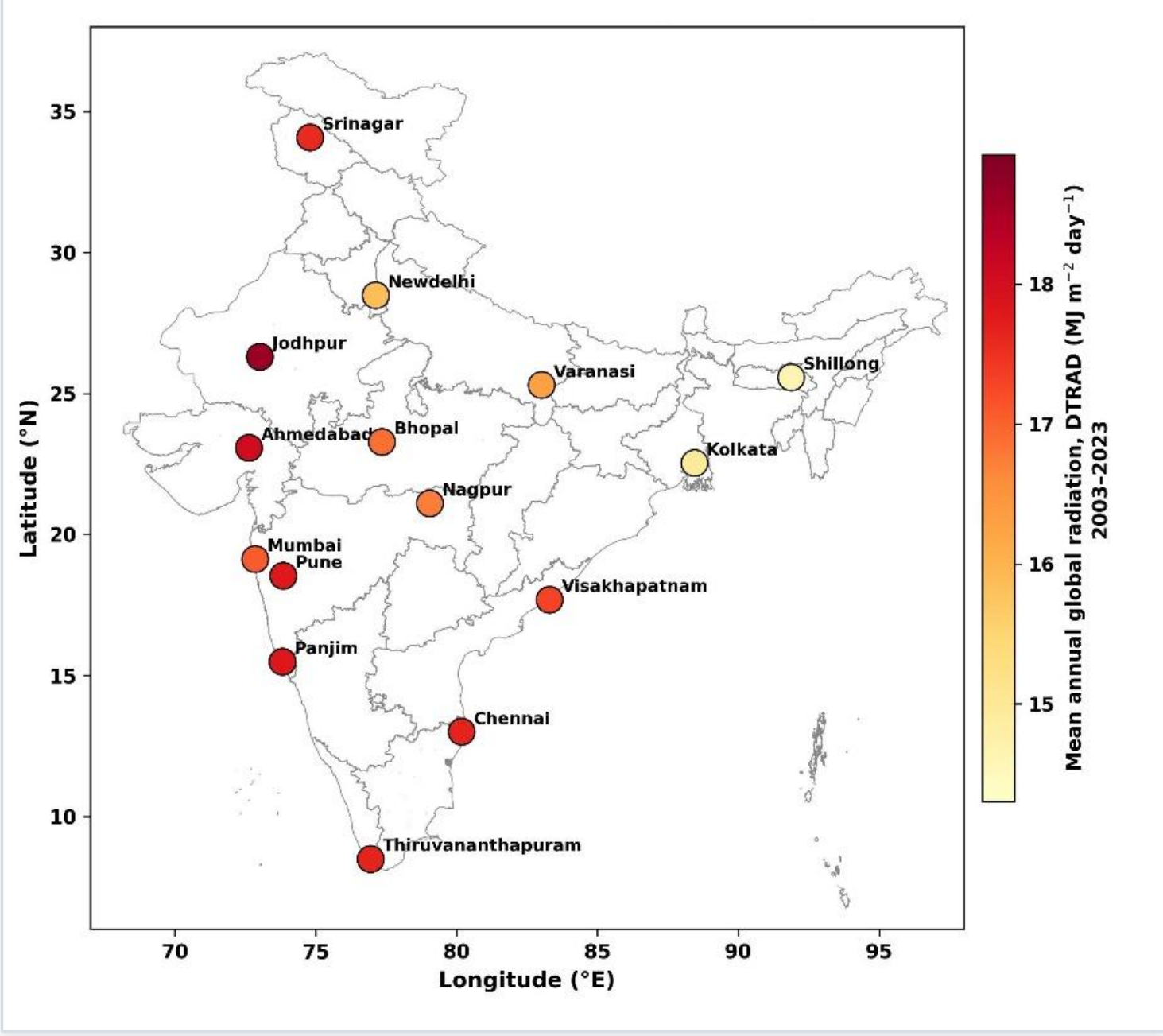


Figure 2. Long-term (2003–2023) mean global radiation, 15-station network (Study B): highest over the arid, cloud-free north-west (Jodhpur, Ahmedabad); lowest over the humid north-east (Shillong, Kolkata), the classic inverse pattern with diffuse radiation.

Discussion: Because this spatial pattern tracks climatology rather than the trend, it is a baseline against which the trend maps in Figures 3–4 should be read: the steepest declines are not simply occurring where radiation is already highest.

54

Years of continuous pyranometer records (1970–2023)

27

Unique IMD stations across both studies combined

2

Reanalysis datasets: ERA5 cloud cover & CAMS AOD₅₅₀

Data & Methods

- ✦ Daily global & diffuse radiation from thermopile and shaded-band pyranometers (290–4000 nm); 10-minute readings averaged to daily means
- ✦ Multi-stage QC: station-year IQR outlier removal, stations with >30% missing data excluded, plus abrupt-spike consistency checks
- ✦ Trend detection: non-parametric Mann–Kendall test ($\alpha = 0.05$) with magnitude from Sen’s slope estimator; OLS shown only for visualisation
- ✦ ENSO phases from the Oceanic Niño Index (ONI): El Niño $\geq +0.5^\circ\text{C}$, La Niña $\leq -0.5^\circ\text{C}$ (3-month running mean, monsoon-aligned)
- ✦ Station-wise Pearson correlation of annual-mean radiation vs. ONI and vs. CAMS AOD₅₅₀, 2003–2023 ($\alpha = 0.05$)

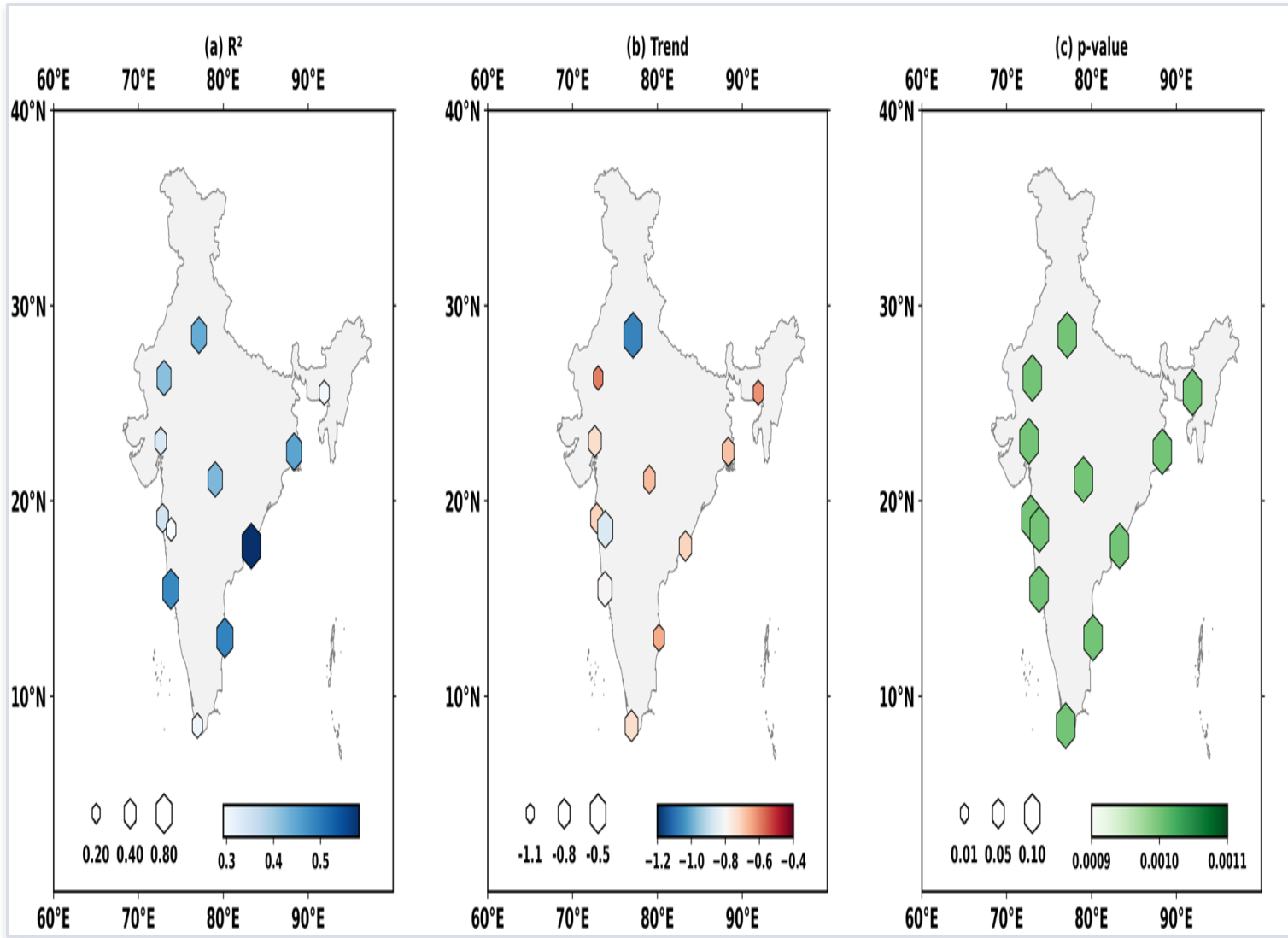


Figure 3. Spatial trend statistics for global radiation, 1970–2023, R^2 , Sen’s slope, and Mann–Kendall p-value at each station. Declines are steepest in the aerosol-heavy north-west.

Discussion: The uniformly small p-values (all green, panel c) confirm every station’s decline is real, not noise; it is the rate of decline, not its existence, that varies regionally.

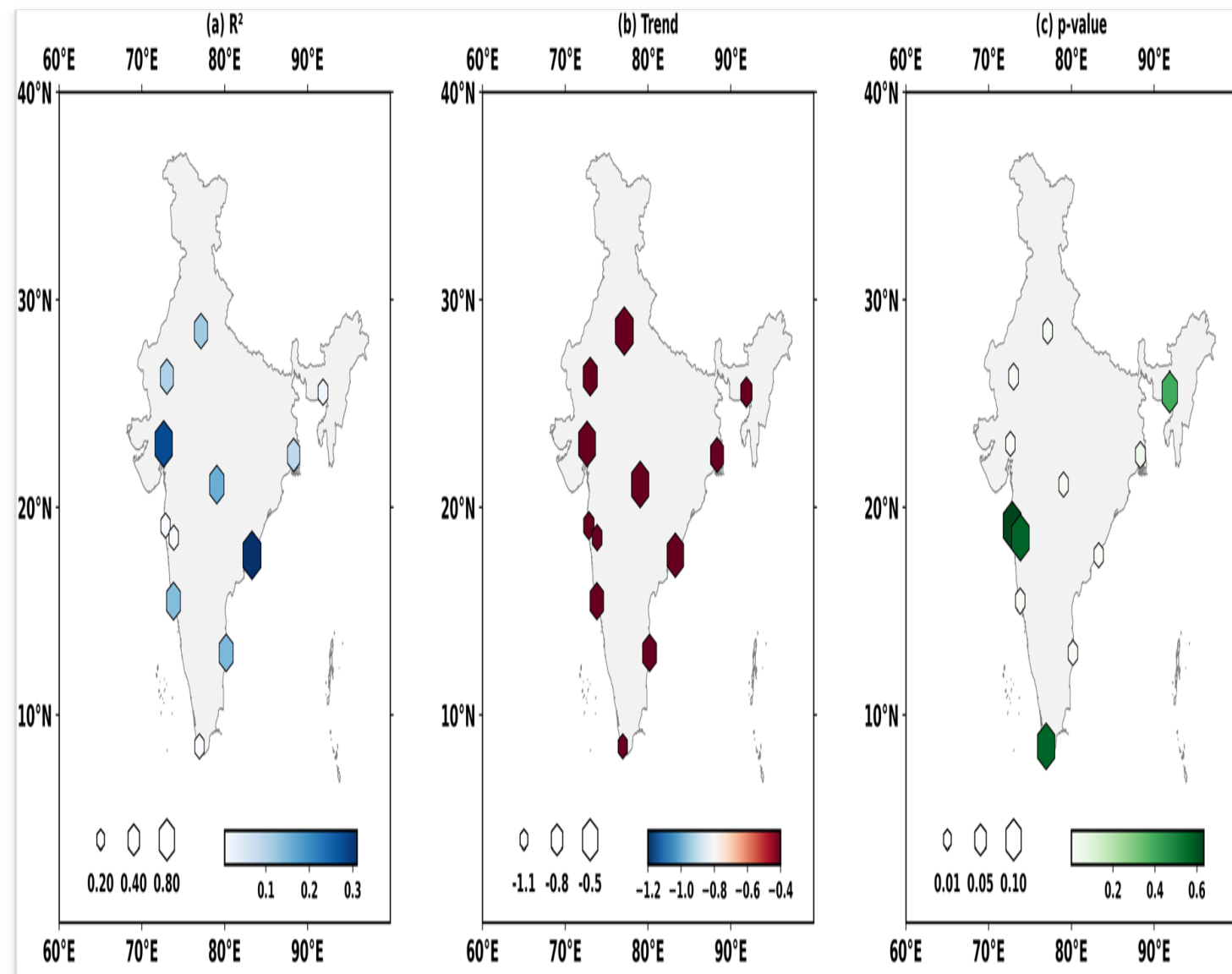


Figure 4. Corresponding trend statistics for diffuse radiation weaker, spatially scattered, and predominantly positive.

Discussion: The mixed p-values (panel c) show diffuse radiation has not yet developed the same nationally coherent signal as the global-radiation decline in Figure 3.

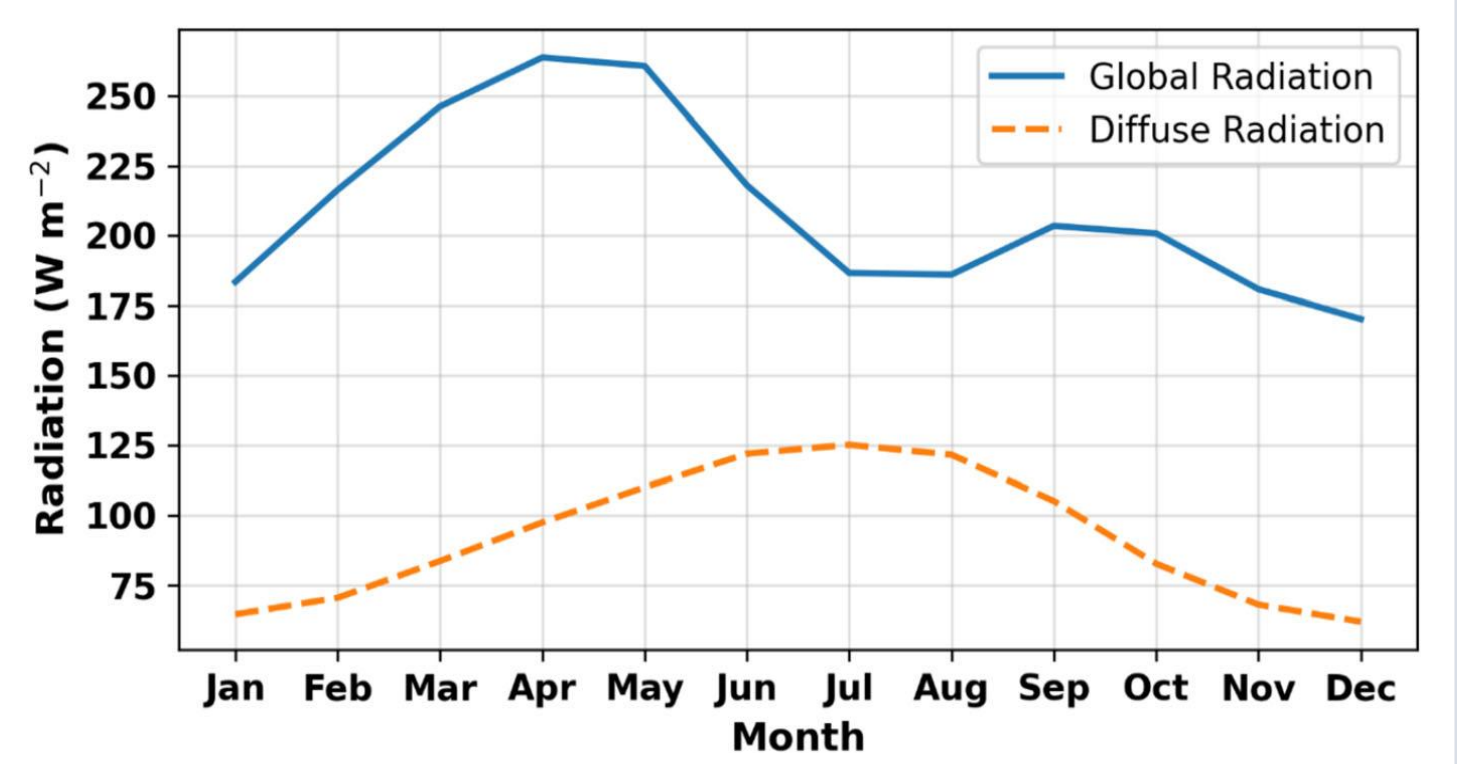


Figure 5. Mean monthly climatologies of global and diffuse radiation, averaged across all stations. Global radiation peaks pre-monsoon (Mar–May); diffuse radiation peaks in the monsoon (Jun–Sep).

Discussion: the near mirror-image shape shows clouds and aerosols redirecting, rather than simply removing, incoming solar energy, the physical basis for the opposite-signed trends in Figures 3 and 4.

Station Network Snapshot

Station	Koppen	Climate
Srinagar	Dsb	Cold, dry-summer continental
Jodhpur	BWh	Hot desert
New Delhi / Ahmedabad	BSh	Hot semi-arid
Varanasi / Bhopal	Cwa	Humid subtropical
Shillong	Cwb	Subtropical highland
Mumbai / Panjim / Trivandrum	Am	Tropical monsoon
Kolkata / Nagpur / Pune / Chennai / Vizag	Aw	Tropical savanna

Study Limitations

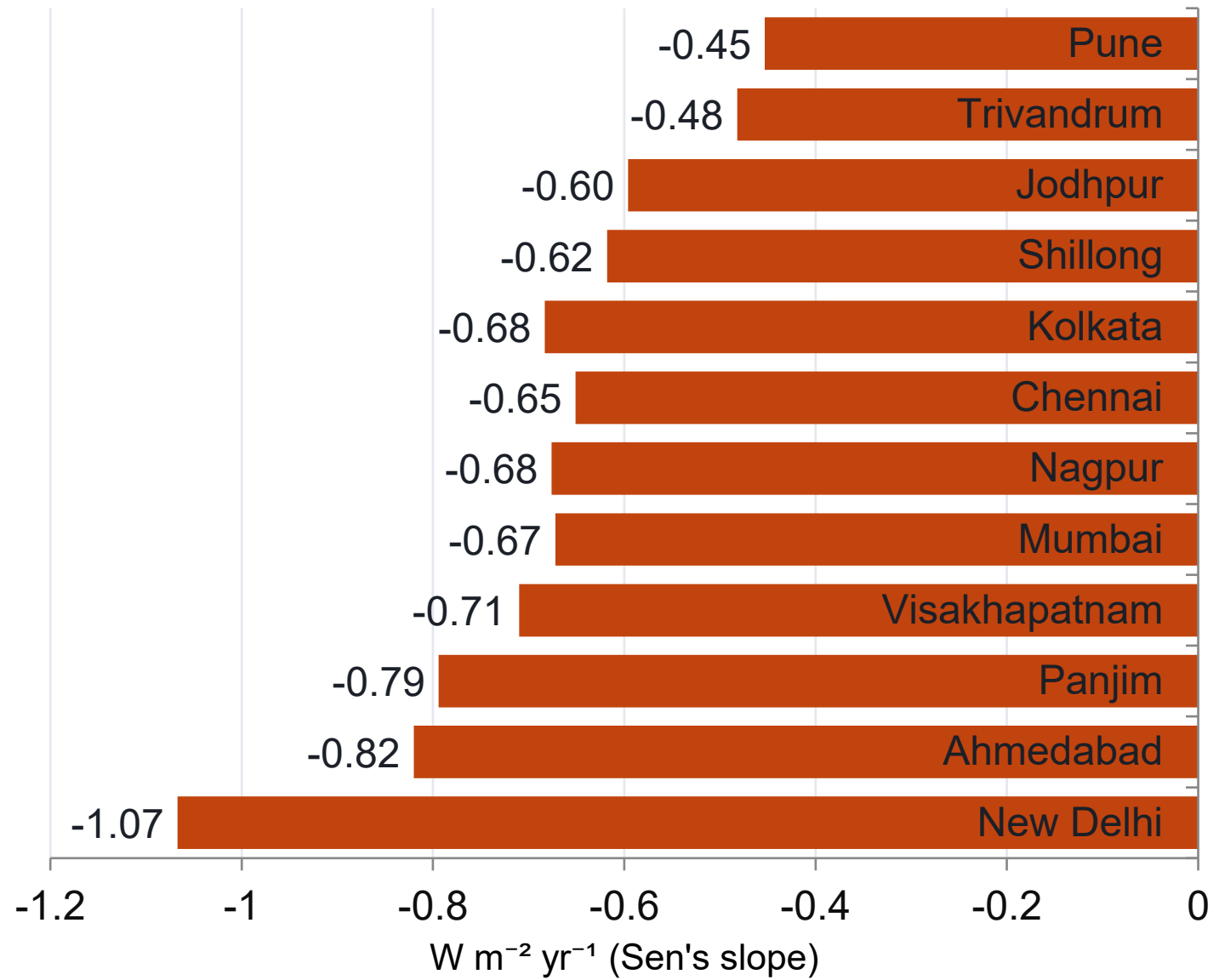
- ✦ No formal homogeneity/breakpoint testing due to incomplete instrument metadata
- ✦ Mann–Kendall does not explicitly correct for residual serial correlation
- ✦ ERA5/CAMS analyses are domain-averaged, large-scale context, not station-level attribution

Results I: Long-Term Dimming (1970–2023)



Annual mean global radiation declined significantly at every one of the 12 long-term stations. Losses are steepest at northern / western stations (New Delhi, Ahmedabad), consistent with rising aerosol loading and urban emissions over the Indo-Gangetic Plain, while coastal / southern stations (Chennai, Trivandrum) show moderated declines, buffered by maritime humidity and monsoon circulation.

Global Radiation Trend by Station ($\text{W m}^{-2} \text{ yr}^{-1}$)



Discussion: Built from the Sen’s-slope values reported for each station, this chart makes the north–south / east–west gradient visually explicit, New Delhi’s decline is more than double Pune’s, despite both lying in the same broad interior climate zone.

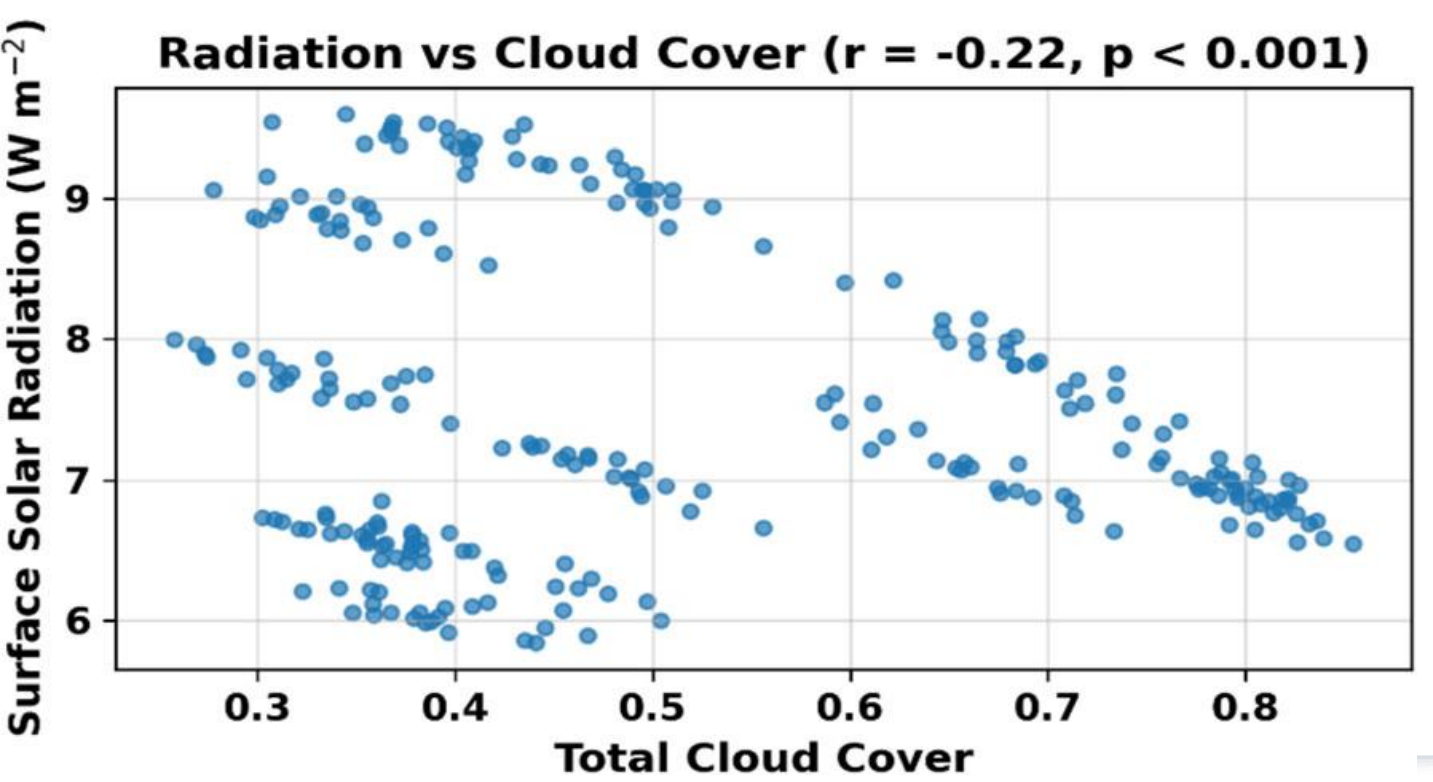
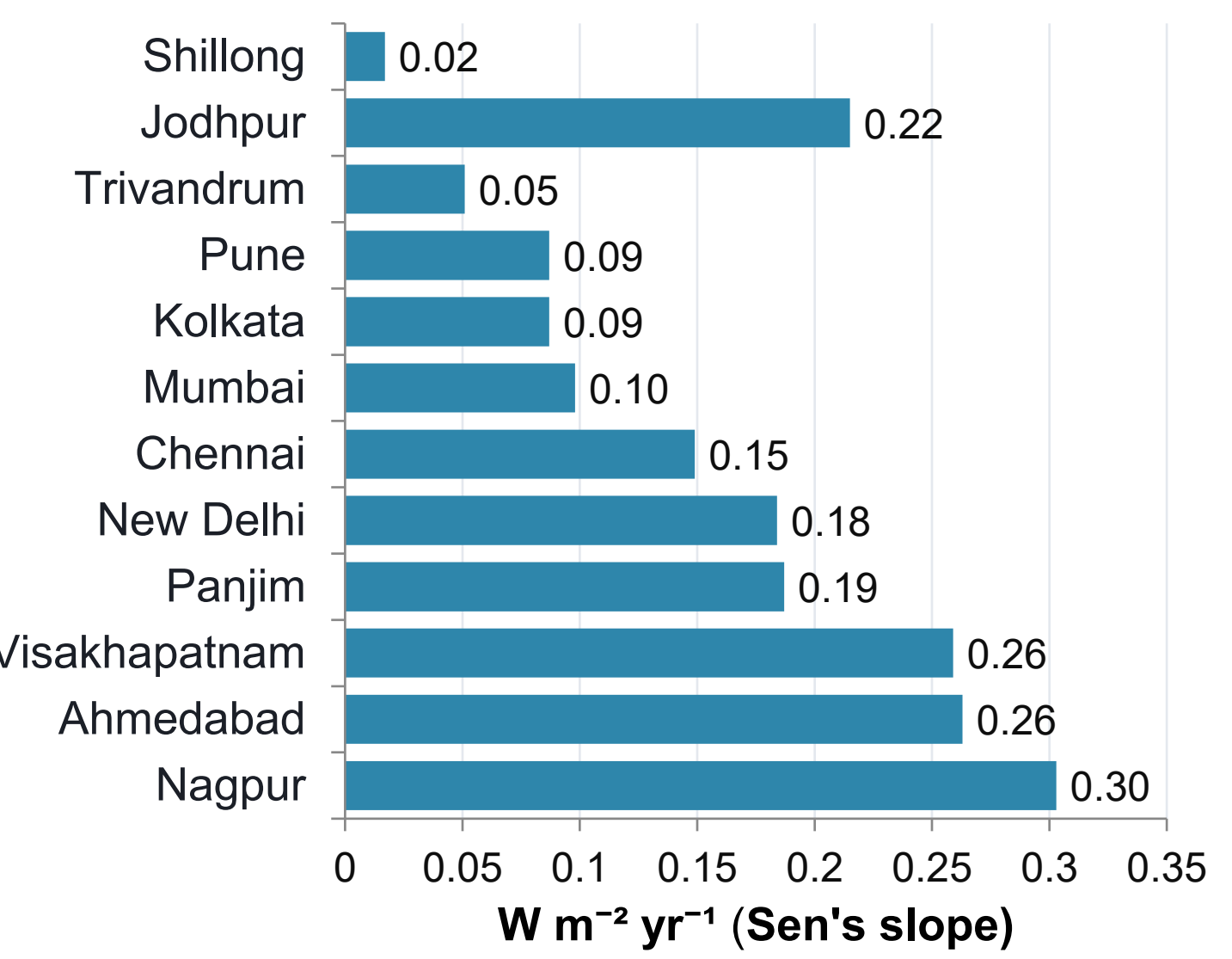


Figure 6. ERA5 total cloud cover vs. surface radiation, 2001–2023: a statistically significant but weak negative correlation ($r = -0.22$, $p < 0.001$).

Discussion: The wide vertical scatter at any given cloud fraction, not a tight line, is the key detail: it shows aerosols and moisture, not cloud cover alone, govern most of the variability, motivating the aerosol analysis in Column 4.

Diffuse radiation shows the mirror-image signal: weak, scattered, but mostly increasing, with significant rises at New Delhi, Ahmedabad, Nagpur, Visakhapatnam, Panjim and Chennai. Diffuse radiation consistently peaks in the monsoon season, as cloud scattering redistributes incoming radiation from direct to diffuse components.

Diffuse Radiation Trend by Station ($\text{W m}^{-2} \text{ yr}^{-1}$)



Discussion: comparing this chart with the one above shows an almost mirror relationship, stations with the steepest global-radiation losses (Nagpur, Ahmedabad, Visakhapatnam) also show the strongest diffuse-radiation gains, exactly as expected if scattering aerosols are converting direct beam into diffuse skylight.

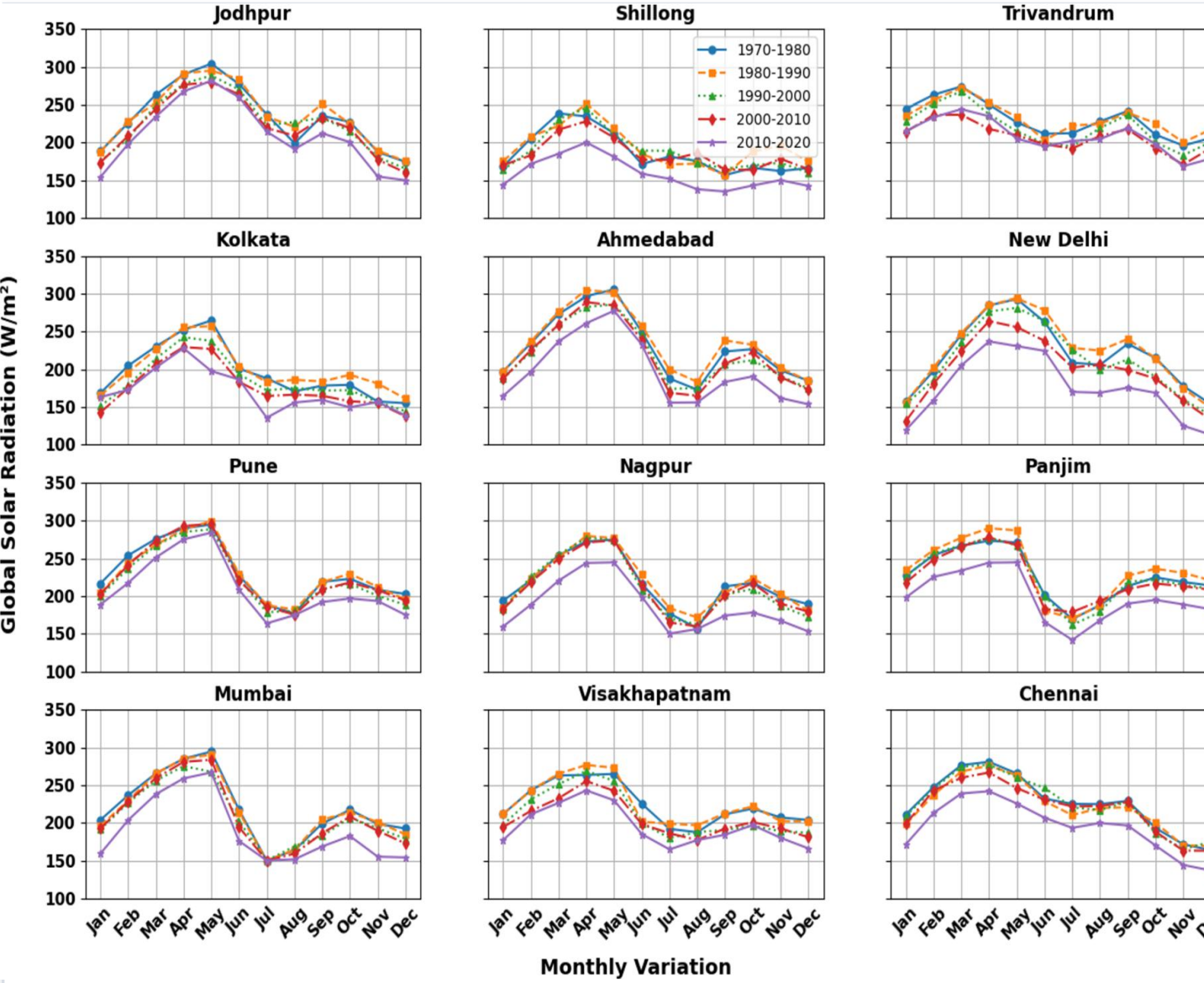
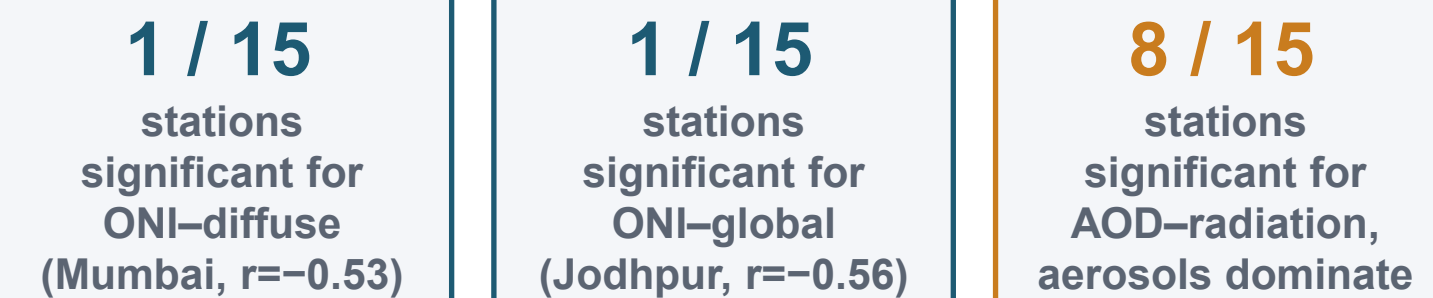


Figure 7. Decadal climatology of global radiation (1970–2023) at all 12 stations: the pre-monsoon peak has flattened and shifted downward decade-on-decade, most visibly at New Delhi, Ahmedabad and Panjim.

Discussion: The decline is concentrated in the pre-monsoon / early-summer peak rather than spread evenly across the year, it points to a seasonal source, consistent with pre-monsoon haze and biomass-burning aerosol loading over northern India.

Results II: ENSO vs. Aerosol (2003–2023)



Percentile and composite analyses show ENSO modulates diffuse and global radiation in a spatially heterogeneous way, arid Jodhpur peaks in El Niño years, humid Srinagar peaks in La Niña years but station-wise Pearson correlation confirms this signal is statistically significant at only 1–2 of 15 stations, explaining at most ~28–31% of interannual variance where detected.

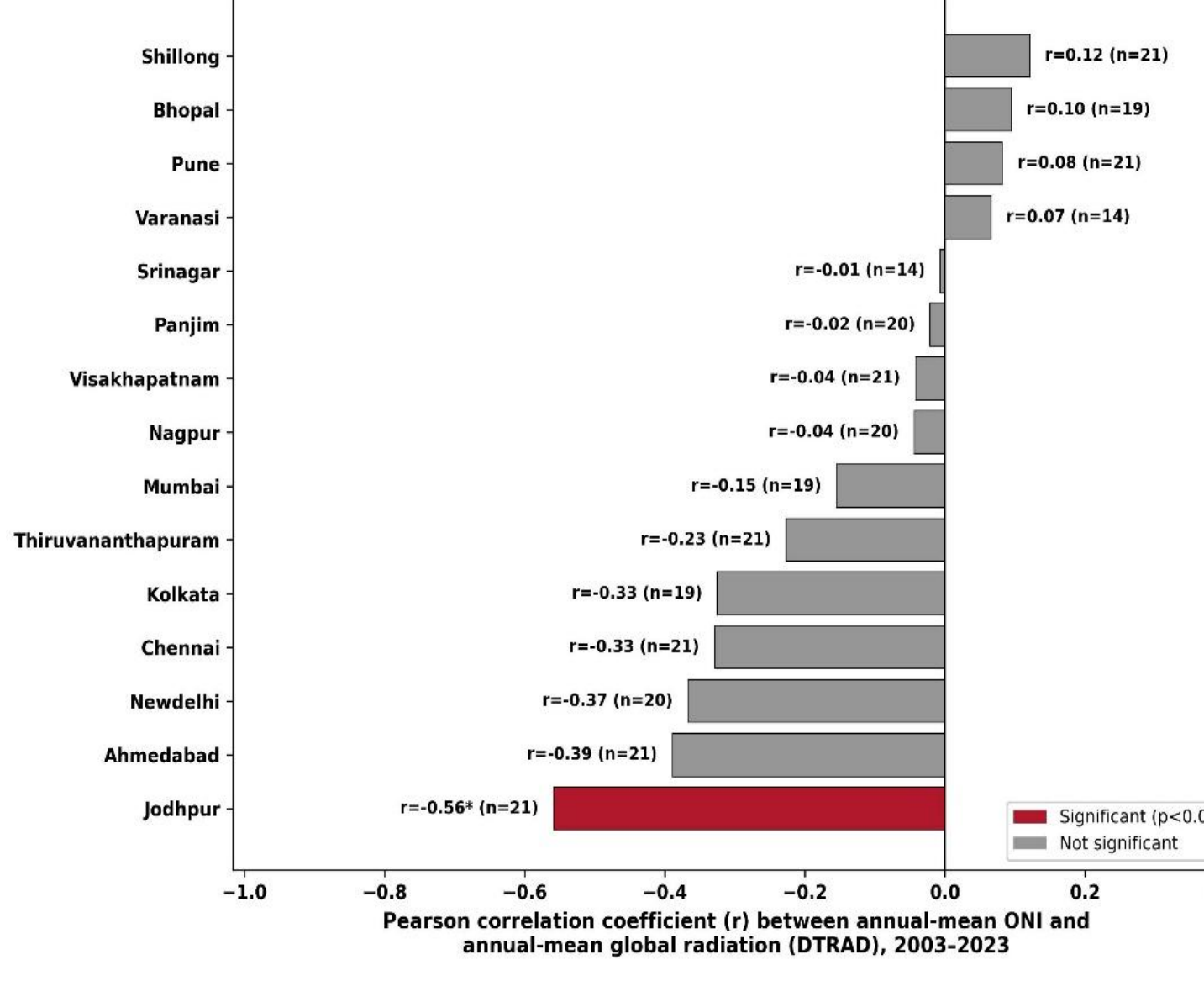


Figure 8. Station-wise Pearson r between ONI and annual global radiation, only Jodhpur is significant, showing ENSO is not a uniform national driver.

Discussion: Jodhpur’s arid, aerosol-light atmosphere makes its cloud cover and hence its radiation unusually sensitive to ENSO-driven shifts in monsoon strength, unlike the aerosol-dominated stations further east.

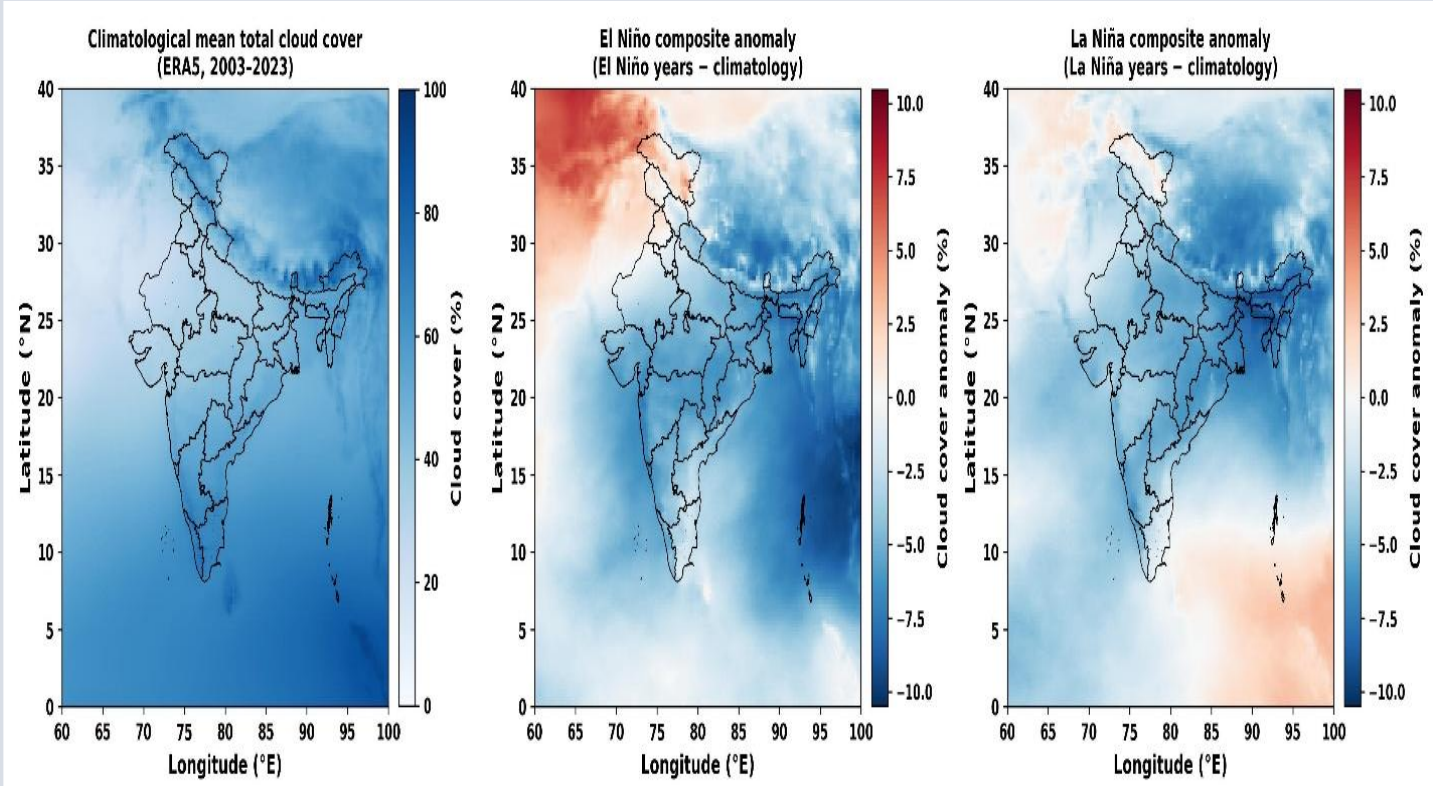


Figure 9. ERA5 cloud-cover climatology and El Niño / La Niña composite anomalies: El Niño suppresses cloud over N/W India, La Niña enhances it.

Discussion: These composite maps supply the physical mechanism, anomalous cloud cover, behind the scattered, mostly-insignificant correlations in Figure 8; the pathway exists but is weak and spatially uneven.

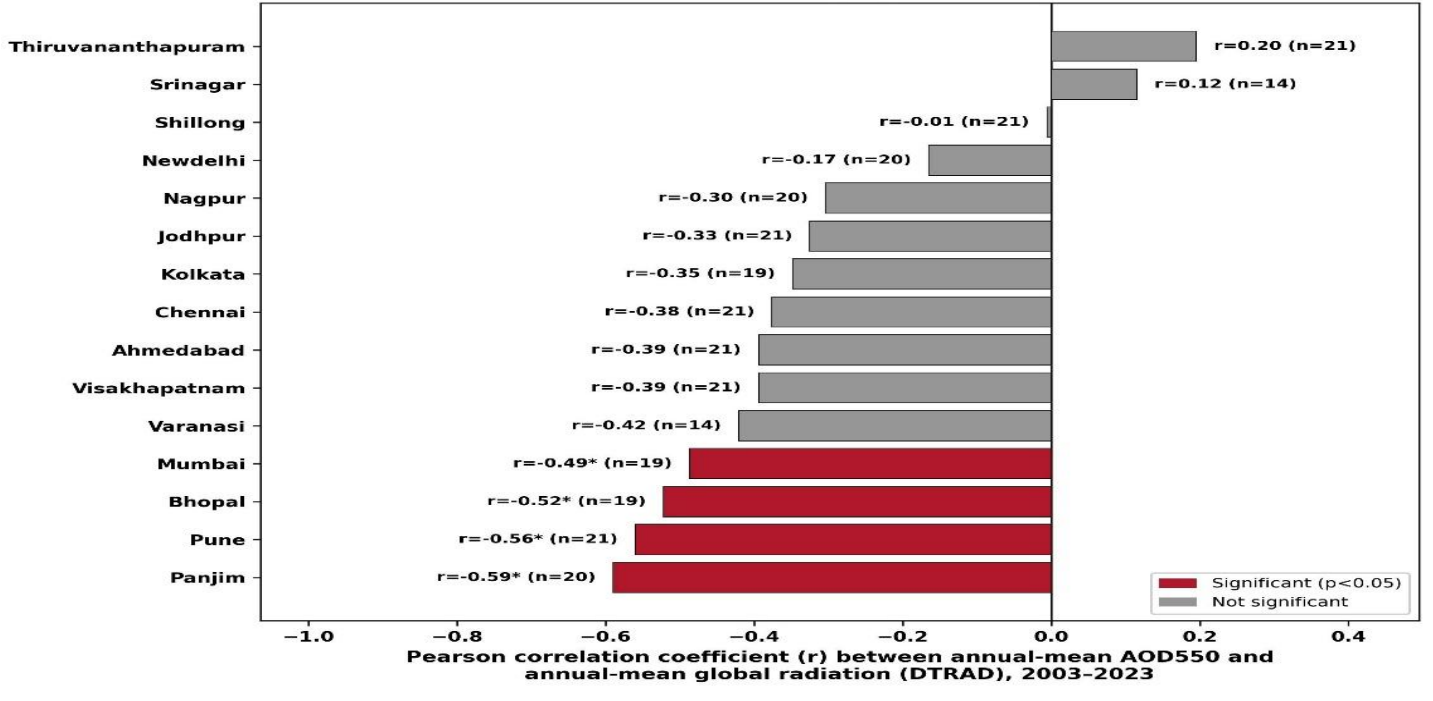


Figure 10. AOD₅₅₀ vs. global radiation: negative at 13 of 15 stations, significant at 4 (Panjim, Pune, Bhopal, Mumbai), a stronger, more consistent signal than ENSO.

Discussion: the fact that nearly every station shows the same negative sign, regardless of climate zone, is the strongest evidence in either study that aerosol loading, not cloud cover or ENSO, is the primary driver of the long-term dimming.

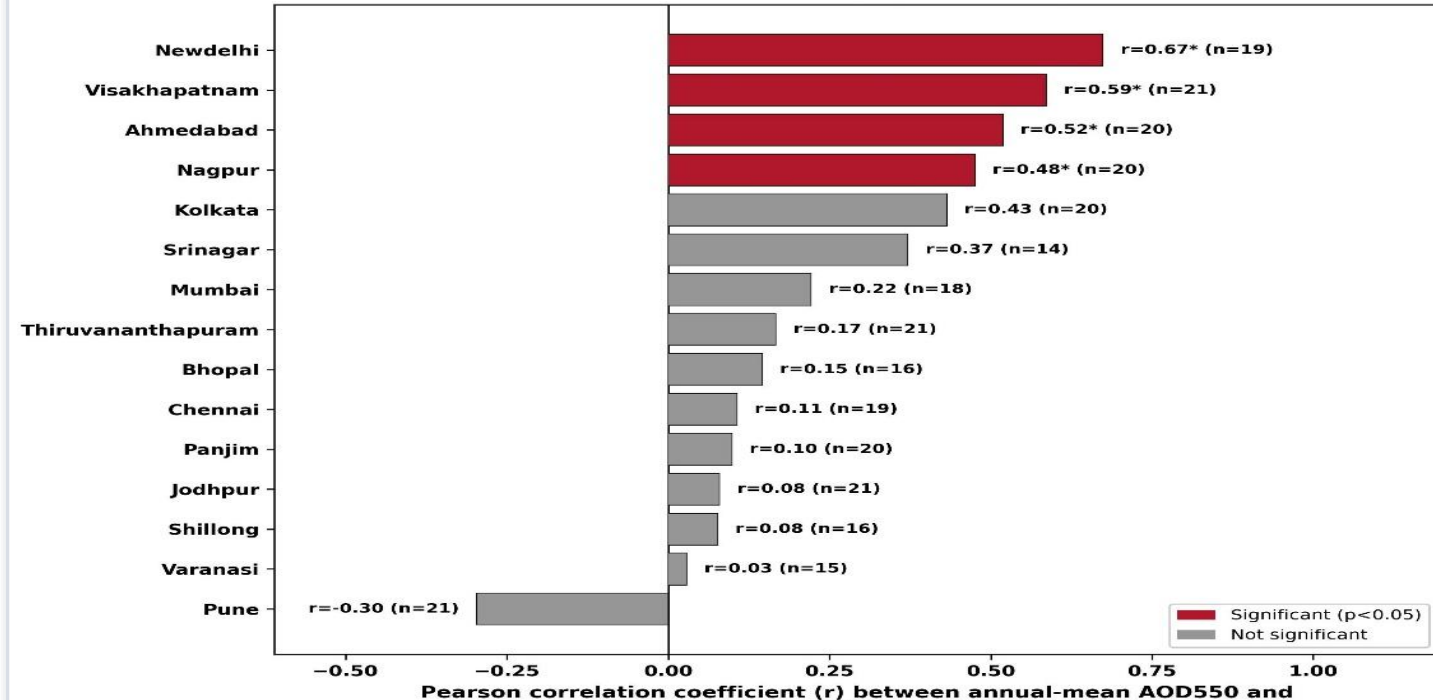


Figure 11. AOD₅₅₀ vs. diffuse radiation: positive at 14 of 15 stations, significant at 4 (New Delhi, Visakhapatnam, Ahmedabad, Nagpur).

Discussion: AOD and diffuse radiation rising together, while AOD and global radiation fall together, is the clearest observational fingerprint of aerosol scattering in the entire dataset, direct sunlight is being converted into scattered skylight, not simply lost.

Conclusions

- ✦ Global SSR declined steadily and significantly at all 12 long-term stations since 1970, with the steepest losses over the aerosol-laden north-west
- ✦ Diffuse radiation shows the mirror-image signal, weak, scattered, but mostly increasing, consistent with growing scattering-aerosol loads
- ✦ ENSO modulates regional cloud cover and radiation, but is significant at only 1–2 of 15 stations, a minor, localized driver
- ✦ AOD correlates far more widely and consistently with both radiation components, anthropogenic aerosol loading is the dominant control on India’s changing solar climate
- ✦ Future work should combine long-term observations with multi-variate aerosol–cloud–moisture reanalysis for formal attribution

Data: India Meteorological Department (National Data Centre, Pune). Reanalysis: ECMWF ERA5; Copernicus Atmosphere Monitoring Service (CAMS).

Sources: <https://doi.org/10.1007/s00024-026-04037-5>