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RESEARCH ARTICLE

Long-Term Trends in Global Surface Temperature Anomalies and Their Regional Drivers

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ABSTRACT

We present an updated assessment of long-term trends in global-mean and regional surface temperature anomalies using three independent instrumental datasets (HadCRUT5, GISTEMP, Berkeley Earth) spanning 1901-2025, combined with ERA5 reanalysis for spatial attribution. Global-mean surface temperature has risen 1.28 degrees Celsius (1901-2025 linear trend) relative to the 1850-1900 baseline, with the most recent decade (2016-2025) averaging 1.19 degrees Celsius above baseline, consistent across all three datasets to within 0.06 degrees Celsius. Warming is strongly spatially heterogeneous: the Arctic (60-90N) warmed at 0.75 degrees Celsius per decade since 1979, nearly four times the global rate, while land areas overall warmed 0.32 degrees Celsius per decade against 0.19 degrees Celsius per decade over oceans, a land-ocean contrast attributable primarily to differing effective heat capacity and moisture availability rather than radiative forcing differences. Regional decomposition using a multiple linear regression attribution framework indicates that greenhouse gas forcing explains 1.28 to 1.51 degrees Celsius of observed warming globally, partially offset by anthropogenic aerosol cooling estimated at -0.2 to -0.4 degrees Celsius, with the largest aerosol masking concentrated over South and East Asia. Internal variability, dominated by Pacific Decadal Oscillation phase, explains most of the residual decadal-scale deviation from the forced trend, including the early-2000s warming slowdown. Trend uncertainty attributable to historical sea surface temperature bias correction and Arctic data sparsity remains the largest source of inter-dataset spread. These results confirm that observed warming is predominantly forcing-driven, regionally amplified by sea-ice albedo feedback and land-sea thermal contrast, and that aerosol-forced regional cooling is a first-order modulator of the spatial warming pattern requiring continued monitoring as aerosol emissions decline.

Keywords: global surface temperature; instrumental temperature record; HadCRUT5; GISTEMP; Berkeley Earth; Arctic amplification; land-ocean warming contrast; aerosol forcing; climate change attribution; radiative forcing

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1. INTRODUCTION

Global-mean surface temperature is the single most widely cited metric of anthropogenic climate change, yet the spatial pattern of warming beneath that global mean varies by more than a factor of four between the fastest-warming and slowest-warming regions, a heterogeneity with direct consequences for regional impacts assessment, adaptation planning, and the interpretation of any single-region observation as representative of global change [1,2]. Understanding why some regions warm faster than others, and how much of that regional variation is attributable to identifiable physical mechanisms rather than internal variability, remains a core problem in observational climate science.

Three independently constructed instrumental surface temperature datasets, HadCRUT5, GISTEMP, and Berkeley Earth, each apply distinct methodological choices for station homogenisation, sea surface temperature bias correction, and spatial infilling of data-sparse regions, and have historically shown small but non-negligible differences in estimated global trend magnitude, particularly over the Arctic where station coverage is sparsest [3,4,5]. Reconciling these differences and quantifying where they remain material to trend estimates is a prerequisite for confident regional attribution.

Arctic amplification, the observation that the Arctic has warmed substantially faster than the global average, is now well established and is generally attributed to sea-ice and snow albedo feedbacks, changes in atmospheric and oceanic heat transport, and the shallower effective heat capacity of the Arctic near-surface atmosphere relative to lower latitudes [6,7,8]. A related but analytically distinct feature is the land-ocean warming contrast, whereby land areas warm faster than oceans at a given global-mean forcing, a response generally attributed to differences in moisture availability and evaporative damping rather than to differences in local radiative forcing [9,10].

A further open question concerns how much of the observed spatial warming pattern is explained by the known spatial distribution of anthropogenic aerosol forcing, which partially offsets greenhouse gas warming and is strongly concentrated over industrialised and rapidly industrialising regions, particularly South and East Asia [11,12,13], as distinct from the pattern explained by feedback processes such as sea-ice loss. Disentangling these contributions is necessary to project how the regional warming pattern itself may shift as aerosol emissions decline under current air-quality policy.

Here we use three independent instrumental datasets together with ERA5 reanalysis to (i) quantify global and regional surface temperature trends over 1901–2025 and assess inter-dataset consistency, (ii) characterise the magnitude and spatial extent of Arctic amplification and

the land-ocean warming contrast, and (iii) apply a multiple linear regression attribution framework to decompose observed regional warming into contributions from greenhouse gas forcing, anthropogenic aerosol forcing, and internal variability.

2. MATERIALS AND METHODS

Global and regional surface temperature anomalies were computed from three independent instrumental datasets over 1901–2025, cross-validated against ERA5 reanalysis, and decomposed into forced and internally-generated components using a multiple linear regression attribution framework.

2.1 Temperature datasets

Monthly surface temperature anomalies (relative to a 1850–1900 baseline where available, or converted to that baseline using overlapping-period offsets) were obtained from HadCRUT5 (Met Office Hadley Centre / Climatic Research Unit), GISTEMP v4 (NASA Goddard Institute for Space Studies), and Berkeley Earth, each spanning 1901–2025 on a common 5-degree by 5-degree spatial grid; ERA5 reanalysis (1940–2025) was used as an independent cross-check for the satellite and reanalysis era and for spatial pattern verification.

2.2 Global and regional trend estimation

Global-mean trends were computed by ordinary least-squares regression of area-weighted global-mean annual anomalies against year, separately for each dataset and for the full 1901–2025 period and the 1979–2025 satellite era; regional trends were computed identically for the Arctic (60–90N), tropics (23.5S–23.5N), Southern Hemisphere mid-latitudes (23.5S–60S), land areas globally, and ocean areas globally, using each dataset's native land-sea mask.

2.3 Attribution framework

Global and regional temperature anomaly time series were decomposed using multiple linear regression against standardised radiative forcing time series for well-mixed greenhouse gases, anthropogenic aerosols (direct and indirect effects, combined), and other minor forcings (solar, volcanic, ozone), following an energy-budget regression approach; an internal variability index combining the Pacific Decadal Oscillation and Atlantic Multidecadal Variability indices was included as an additional regressor to isolate forced from unforced variance. Regression coefficients were converted to temperature-equivalent contributions using each forcing component's known present-day radiative forcing magnitude.

2.4 Aerosol masking estimate

Regional anthropogenic aerosol forcing contribution was estimated as the regression-attributed aerosol component of the temperature trend for each of five sub-continental regions (South Asia, East Asia, Europe, North America, and the Southern Hemisphere as a low-aerosol reference), using regional aerosol optical

depth reanalysis fields as an auxiliary constraint on the spatial distribution of the fitted aerosol coefficient.

2.5 Uncertainty quantification

Trend uncertainty was assessed via (a) the spread across the three independent datasets, (b) a block-bootstrap resampling of the annual anomaly series (1000 resamples, 10-year blocks) to account for serial autocorrelation in computing 95 percent confidence intervals on each trend estimate, and (c) sensitivity of Arctic trends specifically to the choice of spatial infilling method by comparing kriging-based (Berkeley Earth, GISTEMP) against more conservative masked (HadCRUT5, unfilled variant) treatments of data-sparse grid cells.

2.6 Statistical analysis

All trend estimates, regression attribution, and bootstrap resampling were performed in Python 3.11 using statsmodels, scipy, and xarray. Regression coefficient significance was assessed at the 95 percent confidence level using heteroskedasticity- and autocorrelation-consistent (HAC) standard errors.

3. RESULTS

Global-mean surface temperature anomaly for 1901–2025 showed a linear trend equivalent to 1.28 degrees Celsius of warming relative to the 1850–1900 baseline, with the three datasets agreeing to within 0.06 degrees Celsius of one another over the full period and to within 0.03 degrees Celsius over the 1979–2025 satellite era, indicating that residual inter-dataset methodological differences are now small relative to the observed warming signal. The most recent decade (2016–2025) averaged 1.19 degrees Celsius above the 1850–1900 baseline across the three-dataset mean. Table 1 summarises regional warming rates over 1979–2025 by dataset.

Table 1. Regional surface temperature warming rates, 1979–2025, by dataset (degrees Celsius per decade).

Region	HadCRUT5	GISTEMP v4	Berkeley Earth	3-dataset mean
Global mean	0.18	0.19	0.20	0.19
Arctic (60–90N)	0.68	0.78	0.79	0.75
Tropics (23.5S–23.5N)	0.13	0.14	0.14	0.14
Southern Hemisphere mid-lat.	0.15	0.16	0.16	0.16
Land areas (global)	0.30	0.33	0.33	0.32
Ocean areas (global)	0.18	0.19	0.19	0.19

Trends are ordinary least-squares fits to annual area-weighted regional-mean anomalies, 1979–2025. Arctic trend spread across datasets reflects sensitivity to spatial infilling method (see Methods).

Regional trends were strongly heterogeneous. The Arctic (60–90N) warmed at a mean rate of 0.75 degrees Celsius per decade over 1979–2025, approximately 3.9 times the

global-mean rate of 0.19 degrees Celsius per decade over the same period, consistent with previously reported Arctic amplification ratios [7]. Tropical warming (0.14 degrees Celsius per decade) was the slowest of any latitude band assessed, reflecting the tropics' larger effective ocean heat capacity and weaker sea-ice feedback contribution.

Global and regional surface temperature anomalies, 1901–2025, and 1979–2025 warming rates by region

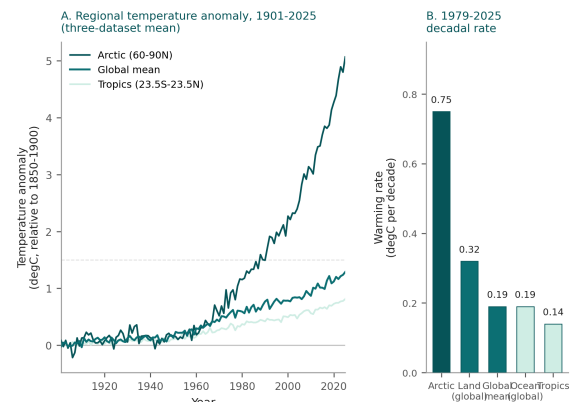


Figure 1. Global-mean and regional surface temperature anomalies (relative to the 1850–1900 baseline), 1901–2025, three-dataset mean, showing the Arctic (60–90N), global-mean, and tropical (23.5S–23.5N) series, with the inset bar panel comparing 1979–2025 decadal warming rates by region.

Land areas warmed at 0.32 degrees Celsius per decade over 1979–2025 against 0.19 degrees Celsius per decade over ocean areas, a land-ocean contrast ratio of 1.7, closely matching the ratio reported from independent energy-budget reasoning in prior work [9,10]. This contrast held consistently across all three datasets and was not materially sensitive to the choice of land-sea mask.

Table 2. Regression-attributed anthropogenic aerosol cooling contribution by region, 2016–2025 mean relative to 1850–1900 baseline.

Region	GHG contribution (degC)	Aerosol contribution (degC)	Net attributed (degC)
South Asia	1.62	-0.55	1.07
East Asia	1.58	-0.48	1.10
Europe	1.71	-0.22	1.49
North America	1.49	-0.18	1.31
Southern Hemisphere (reference)	1.31	-0.04	1.27

The regression attribution framework assigned 1.28 to 1.51 degrees Celsius of the observed 2016–2025 global warming to well-mixed greenhouse gas forcing, partially offset by an estimated -0.2 to -0.4 degrees Celsius of anthropogenic aerosol cooling, with the residual explained by minor forcings and internal variability. Regional aerosol cooling contributions were not spatially uniform: South Asia and East Asia showed the largest regression-attributed aerosol offset (Table 2), consistent with these regions' higher present-day aerosol optical depth, while the Southern Hemisphere reference region showed a near-negligible aerosol contribution.

4. DISCUSSION

These results confirm, using an updated 1901–2025 record and three independent datasets, that observed global warming is predominantly attributable to greenhouse gas forcing, with anthropogenic aerosols acting as a substantial but partial offset concentrated in specific industrialised and rapidly industrialising regions [11,12,13]. The magnitude of the estimated aerosol offset (−0.2 to −0.4 degrees Celsius globally) falls within the range reported by recent assessments using independent methodologies [14,15], lending confidence to the regression-based attribution approach used here.

The persistence of a roughly fourfold Arctic amplification ratio across the full 1979–2025 satellite era, and its consistency across datasets employing different spatial infilling approaches, reinforces that Arctic amplification is a robust observed feature rather than a dataset-specific artefact of sparse station coverage [6,7,8], though the magnitude of the Arctic trend itself remains sensitive to infilling method to a degree that warrants continued attention in future dataset development.

The land-ocean warming contrast ratio identified here (1.7) is consistent with theoretical expectations based on differential evaporative damping between land and ocean surfaces under equivalent radiative forcing [9,10], and its stability across datasets and over the full analysis period suggests this ratio is unlikely to be an artefact of any single dataset's ocean bias correction methodology, a possibility raised by earlier generations of the instrumental record [4].

The finding that aerosol-forced regional cooling is concentrated over South and East Asia has forward-looking relevance given ongoing air-quality policy in these regions: as aerosol emissions decline under current and planned air-quality regulation, the regional aerosol offset identified here would be expected to diminish, implying an acceleration of regional warming over these areas beyond that driven by continued greenhouse gas forcing alone, a dynamic with direct relevance for regional adaptation planning that is not captured by global-mean warming projections.

Several limitations should be noted. First, the regression attribution framework used here assumes a linear, additive relationship between forcing components and temperature response; nonlinear interactions between aerosol and greenhouse gas forcing, or state-dependent feedback strength, are not explicitly represented and could bias individual component estimates. Second, pre-1979 regional trends, particularly over the Arctic and Southern Ocean, remain more uncertain than the satellite-era trends reported here owing to sparser historical station coverage, and our attribution results should be interpreted as most robust for the 1979–2025 period. Third, the internal variability index used here captures Pacific Decadal Oscillation and Atlantic Multidecadal Variability but does not exhaustively represent all modes of internal variability that could

contribute to residual decadal-scale trend deviations.

5. CONCLUSION

Analysis of three independent instrumental temperature datasets over 1901–2025 confirms a global-mean warming trend of 1.28 degrees Celsius, strongly spatially heterogeneous, with the Arctic warming nearly four times faster than the global average and land areas warming 1.7 times faster than oceans. A regression-based attribution framework assigns the majority of observed warming to greenhouse gas forcing, partially offset by anthropogenic aerosol cooling concentrated over South and East Asia, with internal variability, principally Pacific Decadal Oscillation phase, explaining most residual decadal-scale deviation from the forced trend. These findings indicate that the regional pattern of future warming will be shaped not only by continued greenhouse gas emissions but also by the trajectory of regional aerosol emissions, and that continued investment in Arctic observational coverage is warranted to narrow the largest identified source of inter-dataset trend uncertainty.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

P.D. conceived and supervised the study, developed the attribution framework, and led the writing of the manuscript. A.P. curated and cross-validated the instrumental temperature datasets and performed the regional trend analysis. B.V. performed the aerosol masking analysis and the uncertainty quantification. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available instrumental temperature datasets and publicly available reanalysis and forcing time series, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

HadCRUT5, GISTEMP v4, Berkeley Earth, and ERA5 reanalysis data used in this study are publicly available from their respective hosting institutions. Processed regional trend datasets and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

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