

Population Weighted Ambient PM2.5 and O3 Concentrations in China from 2015 to 2024

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Abstract

China has experienced declining fine particulate matter (PM_{2.5}) and persistent ozone (O₃) concerns, but national geographic averages do not describe the concentration distribution where people reside. We conducted an ecological geospatial analysis using annual approximately 1 km ChinaHighAirPollutants PM_{2.5} and O₃ rasters and WorldPop population-count rasters for 2015 to 2024. CHAP values were matched to WorldPop cell centres, and population-weighted ambient concentrations were compared with unweighted geographic means. At 0.2 degree resolution, descriptive linear annual slopes characterized local pollutant trends. Population-weighted PM_{2.5} declined from 53.06 to 31.25 micrograms per cubic metre (41.1%), whereas the corresponding O₃ metric increased from 77.06 to 96.75 micrograms per cubic metre (25.6%). The population-weighted minus geographic-mean difference narrowed for PM_{2.5} from 5.77 to 2.43 micrograms per cubic metre and widened for O₃ from 1.01 to 2.72 micrograms per cubic metre. At the prespecified 0.5 micrograms per cubic metre per year slope threshold, 97.38% of valid blocks had declining PM_{2.5} and rising O₃. The same pattern remained predominant across alternative thresholds. These results describe a broad divergence in population-weighted ambient PM_{2.5} and O₃ concentrations and support reporting both population-weighted and geographic summaries in integrated air-quality assessment.

1 Introduction

Ambient PM_{2.5} and ground-level O₃ are widespread pollutants addressed in contemporary air-quality guidance because of their implications for population health [1, 2]. Their temporal patterns can diverge because they arise from different, interacting emissions and atmospheric processes. China-wide studies have documented declining PM_{2.5} alongside continuing ozone concerns, supporting coordinated PM_{2.5} and O₃ assessment rather than single-pollutant assessment [3, 4].

High-resolution models provide a way to assess changes beyond monitoring locations. The ChinaHighAirPollutants project provides annual PM_{2.5} and O₃ fields at approximately 1 km resolution [5–7]. Prior national studies have assessed population-weighted PM_{2.5} [8, 10], joint PM_{2.5} and O₃ patterns with health burden [3], and ozone exposure inequality [9]. However, a geographic mean gives the same weight to sparsely and densely populated areas. Population weights offer a complementary summary of the ambient concentration distribution across resident locations, while remaining distinct from personal exposure, inhaled dose, regulatory compliance, and health impact.

We combined annual CHAP pollution rasters with WorldPop annual population-count rasters to describe national population-weighted ambient PM_{2.5} and O₃ concentrations in China from 2015 to 2024. We also compared those summaries with geographic means and characterized the spatial distribution of descriptive annual trends.

2 Materials and methods

2.1 Study design and data sources

This ecological repeated-year geospatial analysis covered the China domain represented by the annual CHAP data products from 2015 through 2024. Annual PM_{2.5} Version 4 and O₃ Version 3 GeoTIFF rasters were obtained from the ChinaHighAirPollutants project. The products have approximately 1 km spatial resolution and use the WGS 1984 geographic coordinate reference system. The annual O₃ layer was analysed as the annual concentration metric supplied by CHAP and was not treated as a regulatory exceedance metric.

Annual WorldPop Global2 R2025A population-count rasters for China were used as weights. WorldPop produces these surfaces with a random-forest-informed dasymetric approach that uses census or official population inputs and annual interpolation or projection aligned to national United Nations population estimates [11]. Accordingly, the weights represent modelled resident-population distributions, not observed annual migration or individual mobility.

2.2 Raster matching and concentration summaries

CHAP and WorldPop share a WGS 1984 reference system but have different raster origins and cell sizes. For each year, the CHAP value at the centre of every WorldPop cell was assigned by nearest-neighbour matching. This approach avoids introducing interpolation assumptions beyond the source products. Cells with non-positive population estimates or missing pollutant values were excluded. No administrative boundaries, community coordinates, or individual-level records were used.

For each year and pollutant, the population-weighted ambient concentration was calculated by weighting each valid-cell concentration by its corresponding WorldPop count and dividing the weighted sum by the total valid-cell population. The unweighted geographic mean was calculated over the same valid cells. Their difference was used descriptively to show how population weighting changed the national summary.

2.3 Spatial trend analysis and threshold sensitivity

For spatial visualization, annual CHAP rasters were aggregated into 0.2 degree blocks by arithmetic mean. Within each valid block, an ordinary least-squares slope was estimated from the 10 annual values. Slopes were descriptive and no hypothesis tests were performed. The prespecified transition category of PM_{2.5} decrease and O₃ increase required a PM_{2.5} slope of -0.5 micrograms per cubic metre per year or lower and an O₃ slope of 0.5 micrograms per cubic metre per year or higher. The category analysis was repeated with absolute thresholds of 0.25 and 0.75 micrograms per cubic metre per year to assess sensitivity to this descriptive choice.

2.4 Statistical software and reproducibility

All processing and figures were produced in R version 4.5.1 using the tiff, ggplot2, and patchwork packages. The analysis scripts, processed summary tables, figure files, and R session information accompany this submission. The public source rasters are available directly from CHAP and WorldPop.

3 Results

3.1 National population weighted ambient concentrations

Population-weighted PM2.5 declined from 53.06 micrograms per cubic metre in 2015 to 31.25 micrograms per cubic metre in 2024, an absolute decrease of 21.81 micrograms per cubic metre (41.1%; Table 1 and Fig. 1). In contrast, the population-weighted O3 metric increased from 77.06 to 96.75 micrograms per cubic metre, an absolute increase of 19.70 micrograms per cubic metre (25.6%). O3 rose through 2019, declined modestly in 2020 and 2021, and remained near 97 micrograms per cubic metre between 2022 and 2024.

Table 1
Annual population weighted and geographic mean ambient PM2.5 and O3 concentrations in China from 2015 to 2024 in micrograms per cubic metre

Year	PM2.5 population weighted	PM2.5 geographic mean	O3 population weighted	O3 geographic mean
2015	53.06	47.28	77.06	76.05
2016	49.04	43.77	81.28	80.41
2017	46.45	41.53	88.10	85.97
2018	41.34	37.14	90.06	87.46
2019	39.13	35.23	94.86	91.58
2020	34.71	32.38	91.56	88.82
2021	32.74	30.60	91.31	89.08
2022	31.22	28.99	96.31	92.56
2023	33.01	30.38	96.91	94.46
2024	31.25	28.82	96.75	94.04

Population-weighted concentrations use WorldPop annual population-count estimates as weights. Geographic means are unweighted means across the same valid raster cells.

3.2 Population weighting compared with geographic averaging

Population weighting produced higher national summaries than geographic averaging for both pollutants in every study year (Fig. 2). For PM2.5, the difference narrowed from 5.77 micrograms per cubic metre in 2015 to 2.43 micrograms per cubic metre in 2024. For O3, it widened from 1.01 to 2.72 micrograms per

cubic metre. These quantities describe the population distribution across ambient concentration surfaces and do not estimate personal dose or health risk.

3.3 Spatial annual trends

Across 24,938 valid 0.2 degree blocks, the median PM2.5 linear annual slope was – 1.82 micrograms per cubic metre per year and the median O3 slope was 1.99 micrograms per cubic metre per year (Table 2 and Fig. 3). At the prespecified 0.5 micrograms per cubic metre per year threshold, 24,285 blocks (97.38%) were classified as PM2.5 decrease and O3 increase. This pattern remained predominant at alternative absolute thresholds of 0.25 (99.25%) and 0.75 (92.12%) micrograms per cubic metre per year (Supplementary Table S2).

Table 2
Distribution of descriptive linear annual trend slopes across valid 0.2 degree blocks

Metric	Valid blocks	Median slope	25th percentile	75th percentile
PM2.5 linear trend	24938	-1.82	-2.74	-1.23
O3 linear trend	24938	1.99	1.52	2.84

All slopes are in micrograms per cubic metre per year. The interquartile range is represented by the 25th and 75th percentiles.

4 Discussion

Using a common high-resolution population-weighted framework, we observed lower national ambient PM2.5 concentrations and higher O3 concentrations between 2015 and 2024. The opposing pattern was evident in the national summaries and in the median local slopes. It was also retained when the descriptive threshold used to define the paired trend category was made more or less stringent. This pattern is consistent with the need for coordinated PM2.5 and O3 assessment reported in prior China-wide work [3, 4].

The comparison of population-weighted and geographic means adds a clear interpretation. In this dataset, an unweighted geographic average increasingly understated the population-weighted O3 summary, whereas the corresponding difference for PM2.5 narrowed. Reporting both measures can therefore show whether a national map average represents the concentration distribution across residents. It does not establish an individual exposure distribution because residents move, spend time indoors, and do not experience a single annual ambient concentration.

This analysis does not assess why the two pollutants changed. PM2.5 and O3 respond to precursor emissions, atmospheric chemistry, meteorology, and regional transport. The present design did not include precursor emissions, meteorological covariates, policy indicators, or health outcomes, and it cannot support causal or health-impact inferences.

Several limitations should guide interpretation. First, CHAP concentrations and WorldPop counts are modelled geospatial products and have uncertainty. Second, the annual WorldPop surfaces are estimates based on census or official inputs plus interpolation or projection and cannot be read as observed fine-scale migration. Third, the CHAP annual O₃ metric cannot evaluate seasonal or short-term regulatory exceedance. Fourth, nearest-neighbour matching avoids unsupported interpolation but does not remove all effects of grid misalignment. Finally, the analysis did not use administrative boundaries or local monitoring data to validate subnational estimates.

5 Conclusions

From 2015 to 2024, China's population-weighted ambient PM_{2.5} concentration declined from 53.06 to 31.25 micrograms per cubic metre, while the corresponding O₃ metric increased from 77.06 to 96.75 micrograms per cubic metre. The predominant spatial trend was decreasing PM_{2.5} with increasing O₃. Population-weighted ambient concentration summaries should complement geographic averages in integrated assessment of particle and photochemical pollution.

Declarations

Ethics approval and consent to participate:

Not applicable. This study analysed publicly available environmental and modelled population raster data only; it involved no human participants, human data, biological material, or animals.

Consent for publication:

Not applicable.

Competing interests:

The authors declare that they have no competing interests.

Authors' contributions

Debo Xu conceived the study, designed the research and acquired funding. Xiaowei Mai performed the statistical analysis, prepared the visualisations and wrote the first draft. Zhenyu Liang, Lin Li curated the data, revised the manuscript and provided supervision. All authors, including Junyi Xia, reviewed and approved the final manuscript.

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Author Contribution

Debo Xu conceived the study, designed the research and acquired funding. Xiaowei Mai performed the statistical analysis, prepared the visualisations and wrote the first draft. Zhenyu Liang, Lin Li curated the data, revised the manuscript and provided supervision. All authors, including Junyi Xia, reviewed and approved the final manuscript.

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All authors have read, understood, and have complied as applicable with the statement on Ethical responsibilities of Authors as found in the Instructions for Authors.

Data availability:

CHAP annual PM_{2.5} and O₃ data are publicly available from <https://chap-data.github.io/introduction.html>. WorldPop Global2 R2025A annual population-count rasters are publicly available from <https://hub.worldpop.org/project/categories?id=3>. The R code, processed summary tables, and figure files used in this study are supplied with this submission. Source rasters are not redistributed because they are available directly from their original providers.

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Figures

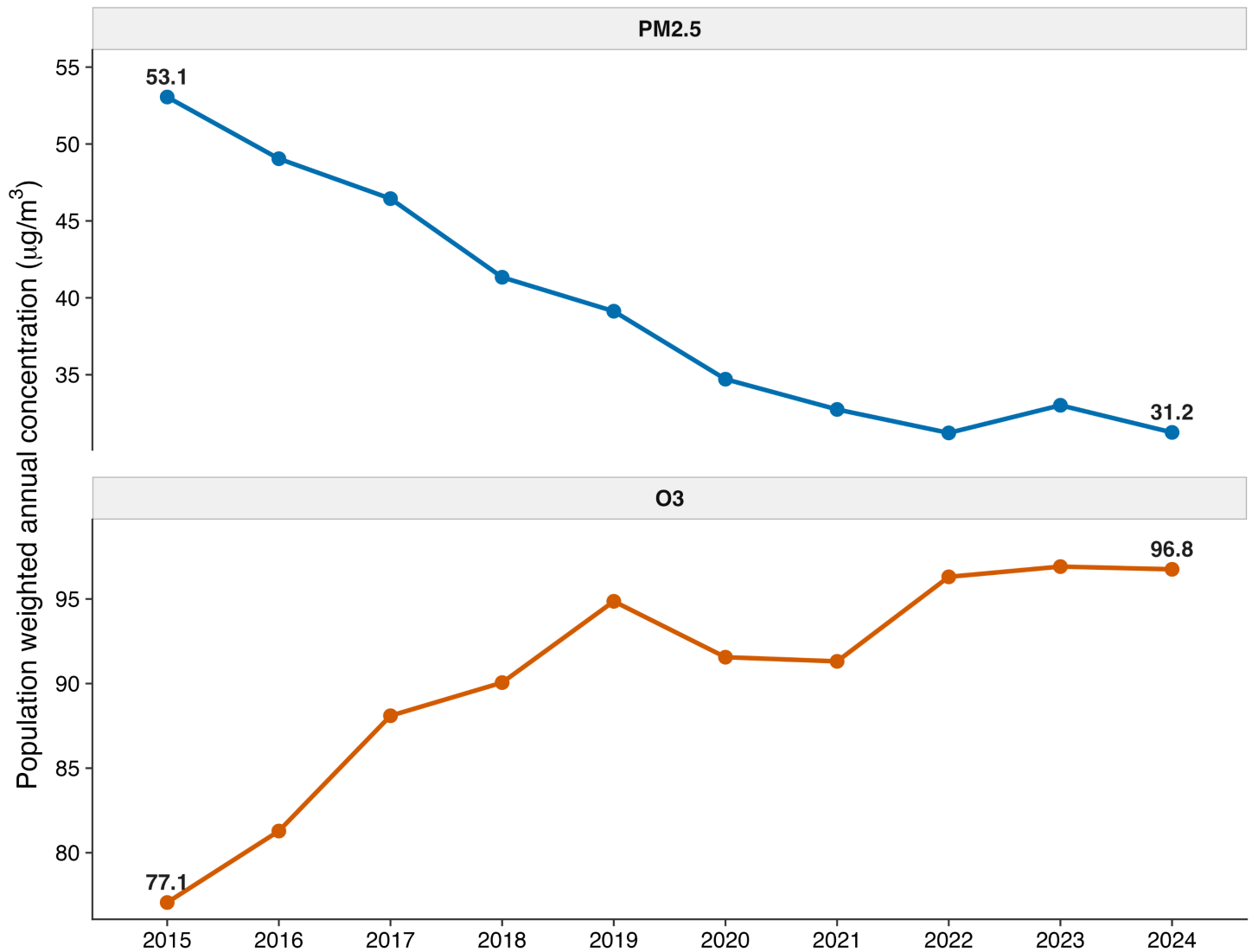


Figure 1

National annual population-weighted ambient PM2.5 and O3 concentrations in China from 2015 to 2024. End-point values are labelled in micrograms per cubic metre.

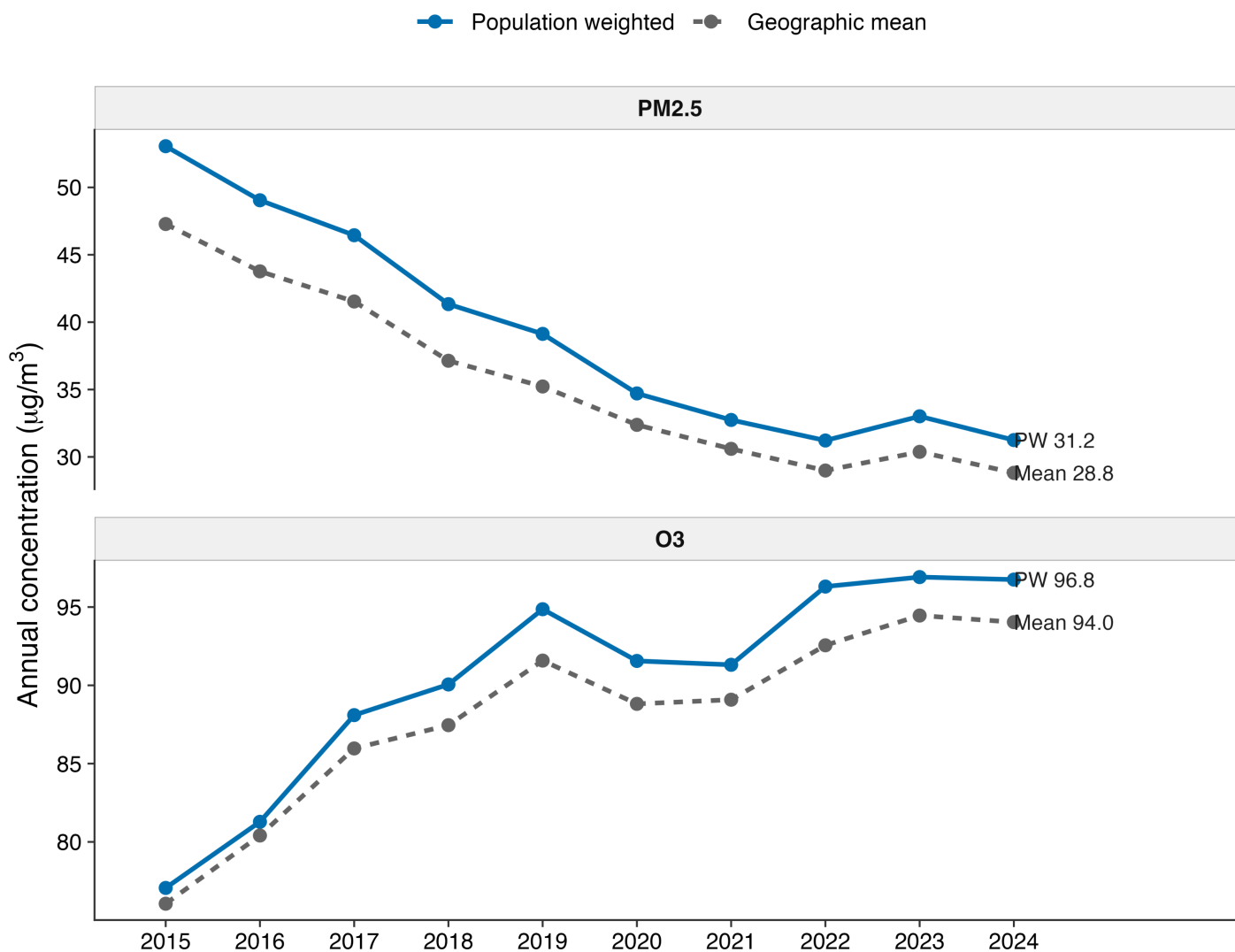


Figure 2

Annual population-weighted and geographic-mean ambient concentration summaries. Population-weighted values are shown in blue and geographic means in grey; direct labels show the 2024 values.

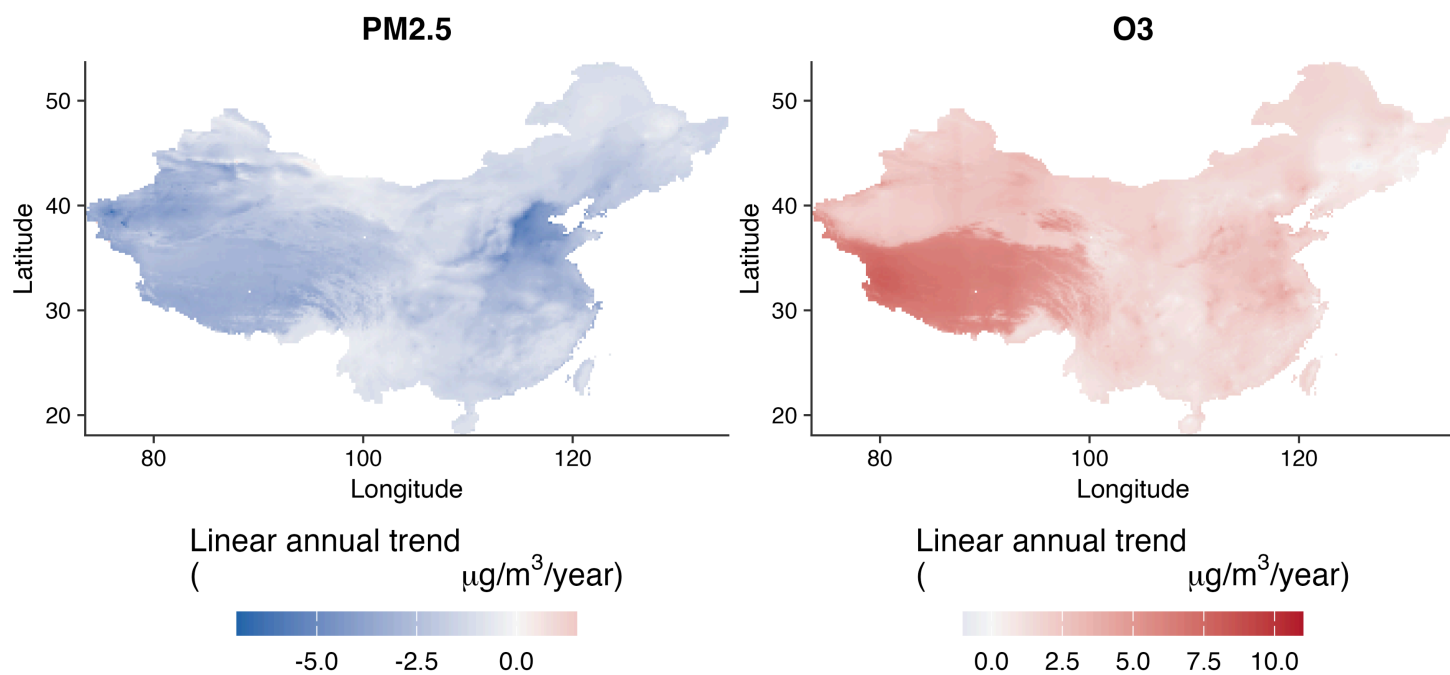


Figure 3

Spatial distribution of linear annual trends in PM2.5 and O3 concentration metrics from 2015 to 2024. Each raster cell represents a valid 0.2 degree block; blue denotes decreasing and red denotes increasing concentrations.