Supplementary Materials

Current Status, Trends and Future Directions in Chilean Air Quality: A Data-Driven Perspective

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The supplementary material presents data on the computing methods used in **Section S1**. **Section S2** shows Chilean air Quality legislation limits and emergency levels. Table S1 defines the classification of contamination events by listing threshold values for $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3. The table assigns emergency levels through a color-coded system and includes a reference to the official web page used for monitoring these events. This table establishes the criteria that guide the activation of environmental alerts and serves as a reference for comparing observed pollutant levels. On the other hand Table S2 shows the emergency levels and the respective legislation.

Section S3 shows air quality monitoring in Chile through a series of tables and figures that explain the structure and behaviour of pollutant concentrations over time and space. Figures S1 through S7 show information on the **location of monitoring stations and typical pollutant concentrations**. For example, one figure maps the position of stations in selected industrial zones and overlays this information with human settlement and census population data. Other figures display daily measurements of SO_2, CO, O_3, NO_x, NO, and NO_2 across different macrozones. Additional figures report median values of SO_2, CO, and $PM_{2.5}$ from specific monitoring sites, which supports the understanding of pollutant behaviour in various locations.

Figures S8 to S18 provide a view of the **cycles of pollutant concentrations recorded on hourly, daily, and monthly scales**. These figures illustrate the variation in pollutant levels throughout the day and across different days and months, including an analysis of the central region that excludes the metropolitan area of Santiago. This cyclic information aids in identifying regular patterns in pollutant behaviour and the influence of factors such as traffic, industrial activity, and meteorological conditions. Furthermore, Figures S19 to S21 illustrate the **calculated trend for all the monitoring stations with available information between 2000 and 2024**.

In **Section S4**, Tables S3 through S10 compile the results of **national trend analyses for PM_{10}, $PM_{2.5}$, SO_2, CO, O_3, NO_x, NO, and NO_2 over a 24-year period**. Each table presents the rate of change in pollutant concentrations along with the corresponding statistical significance for each macrozone. These tables provide numerical records of long-term trends, allowing for an assessment of how pollutant levels have shifted over time in different regions of Chile.

Section S1 Materials and Methods: Software and computational tools

This study employed a Python environment (Python Software Foundation. Python Language Reference, version 3.9. Available at http://www.python.org) to manage data extraction, processing, and analysis. This approach was selected due to Python's capacity for handling large datasets, integrating diverse libraries for geospatial and statistical tasks, and facilitating reproducible workflows in atmospheric sciences [45,46,47]..

NumPy [48] and pandas [46] were used for array-based and tabular operations, and matplotlib [47] generated plots. Requests [49], urllib, and managed network interactions, while Beautiful Soup [50] handled HTML parsing. GeoPandas [51] and shapely [52] enabled geospatial analysis by incorporating shapefiles (administrative boundaries, census data, land-cover maps). Time series trend detection employed PyMannKendall [53] to perform the non-parametric Mann-Kendall (MK) test. Quality control (outlier detection, unit conversion, consistency checks) was conducted using custom Python functions alongside pandas and NumPy.

Automated Extraction and Verification of SINCA Data to Local Data-base

SINCA hosts real-time and historical air quality data for multiple locations in Chile. Users can download individual station files, but this requires manual navigation and separate retrieval for each pollutant. A Python-based web scraping tool was developed to reduce the effort associated with data collection. The script traverses all relevant SINCA pages, downloads CSV files for each pollutant at each of the 218 monitoring stations, and stores them in a centralized directory. Station details—official names, latitudes, and longitudes—are managed by a Python dictionary. This work focuses on criteria pollutants (PM_{10}, $PM_{2.5}$, CO, SO_2, O_3, NO_x, NO, and NO_2) collected between January 1, 1993 01:00 (UTC – 4), and December 31, 2024 23:00 (UTC – 4). Less frequently measured parameters (Pb, As in particulate matter, hydrocarbons) and meteorological observations fall outside the scope of this study. The raw data consists of 1744 CSV files, each containing date, hour, and pollutant concentrations.

Following download, a pre-processing phase identifies missing or spurious measurements, standardizes units, and unifies date formats (dd/mm/yyyy hh). Processed files are then consolidated into NumPy arrays, creating a single dataset of 3260 MB). This procedure enhances data accessibility and facilitates subsequent analyses.

Completeness and spatial coverage assessment

A completeness assessment was performed for each pollutant and station, identifying periods with insufficient data. Stations with at least 75% data coverage since their start date were prioritized for further analysis. All available measurements (preliminary, unvalidated, validated) were compiled into continuous time series, with flags to differentiate validated records.

Spatial coverage was evaluated by comparing station locations (Table 1) to national population density, considering Chile's varied geography (Andean highlands, desert regions, forested south). Figure 2 highlights five industrial–urban corridors, emphasizing the intersection of industrial activities with populous areas. Shapefiles from the 2017 national census (https://ideocuc-ocuc.hub.arcgis.com/), land-cover maps (https://chile.mapbiomas.org/), and pollutant datasets help illustrate how industrial operations, demographic patterns, and elevated air pollution levels

converge in “sacrifice zones.” Although exposure impacts are not calculated, the distribution of stations and how the data may vary in these zones can help to indicate whether local pollution sources are adequately monitored.

Temporal distribution, standard compliance

Temporal variation of air pollutants was explored at hourly, daily, and monthly scales to characterize diurnal, weekly, and seasonal trends. Concentration data were used to identify pollution episodes and regions with persistently elevated values. Interannual changes were examined by computing 90th percentiles of hourly, daily, and monthly records, allowing detection of consistent high-concentration periods within each time series. Regional or macro-zonal time series were generated by averaging station data to facilitate broader spatial comparisons.

Priority was given to $PM_{2.5}$ and SO_2 due to longer measurement records and relevance to public health. Concentrations were compared to Chilean air quality standards and World Health Organization (WHO) guidelines (Table 2). This comparison identified critical intervals or areas potentially associated with health risks.

Trend analysis

To assess long-term variations in air quality and identify potential improvements or deteriorations, time series analyses of pollutant concentrations was performed. Trends were evaluated using the Mann-Kendall (MK) test [45], a robust non-parametric method capable of delivering reliable estimates even when outliers are present in the data. This approach calculates the median of all possible slopes between observations, offering a clear measure of both the direction and magnitude of changes over time. The Pymannkendall library in Python [53] was employed to carry out the MK test on daily median concentrations, focusing on the specific hours when peak values typically occur. Stations with a completeness level exceeding 75% were included in the analysis. For clarity, results are presented in a north-to-south format across the five defined study regions, facilitating a comprehensive comparison of spatial trends.

Section S2: Chilean Air Quality Limit levels and Event Classifications

Table S1. International (World Health Organization, WHO) and Chilean air quality limit levels for NO_2, SO_2, CO, O_3, $PM_{2.5}$, PM_{10}. NO_2, SO_2 and O_3 are always reported as ppbv and CO as ppmv.

Limits	NO_2 ppbv	SO_2 ppbv	CO ppmv	O_3 ppbv	PM_{10} µg/m³	$PM_{2.5}$ µg/m³
ClNAQS Annual	21.3 (40 µg/m³)	23 (60 µg/m³)			50	20
ClNAQS 24-Hour	53.2 (100 µg/m³)	57 (150 µg/m³)			130	50
ClNAQS 1-Hourly	106.4 (200 µg/m³)	134 (350 µg/m³)	26 (30 mg/m³)			
ClNAQS 8-hourly			9 (10 mg/m³)	61 (120 µg/m³)		
WHO 24- Hour (54)* (WHO guidelines are all in µg/m³)	13.3 ppbv 25 µg/m³	15.3 ppbv 40 µg/m³	3.2 ppmv 4 mg/m³	(8 hour) 50 ppbv 100 µg/m³	45 µg/m³	15 µg/m³
WHO Annual (54)* (WHO guidelines are all in µg/m³)	5.3 ppbv 10 µg/m³				15 µg/m³	5 µg/m³
References	(55)	(56)	(57)	(58)	(59)	(60)

*****Air Quality Guideline level (even there are interim targets that are significantly higher)

Table S2. Chilean classification of contamination events, showing threshold values for $PM_{2.5}$ (24-hour), PM_{10} (24-hour), CO (8-hourly), NO_2 (hourly), SO_2 (hourly), and O_3 (hourly) and the corresponding emergency levels assigned via a color-coded system. The table also includes a reference to the official monitoring website.*

Emergency levels	$PM_{2.5}$ µg/m³ (24 hour)	PM_{10} µg/m³ (24 hour)	CO ppmv ** (8 Hourly)	NO_2 µg/m³ (Hourly)	SO_2 ppbv ** (Hourly)	O_3 ppbv ** (Hourly)
Level 1			15-29	500-799		204-407
Level 2			30-34	800-1399		408-509
Level 3			≥ 35 ppm	≥ 1400		≥ 510
Good	0-50					
Regular	51-79					
Alert	80-109	180-229			191-247	
Pre-emergency	110-169	230-329			248-362	
Emergency	≥ 170	≥ 330			≥ 363	

* https://normasaire.mma.gob.cl/nambientales/normas-de-calidad-del-aire.

**Conversion from ppbv to µg/m³ for O_3, NO_2, SO_2 are 1 ppb = 1.96 µg/m³ for O_3, 1ppbv = 1.88 µg/m³ for NO_2, 1ppbv = 2.62 µg/m³ for SO_2 at 25°C and 1 atm and for CO, 1 ppmv = 1.25 mg/m³ 25°C and 1 atm.

Section S3: Supplementary Figures

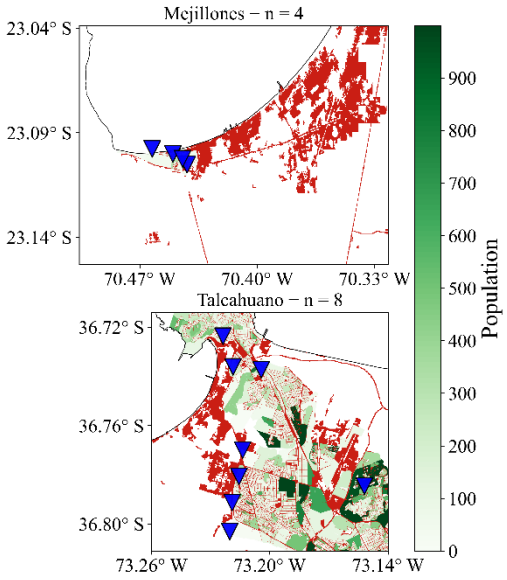


Figure S1. Map displaying the location of monitoring stations in selected industrial zones (Talcahuano at the top -Zona Central Macrozone - and Mejillones at the bottom -both in the Zona Central Macrozone). Human settlements are marked in red, while population data from the 2017 census appear in green, with "n" indicating the number of monitoring stations. Station locations are shown as blue triangles. Settlement data are adapted from https://chile.mapbiomas.org/ data for 2022.

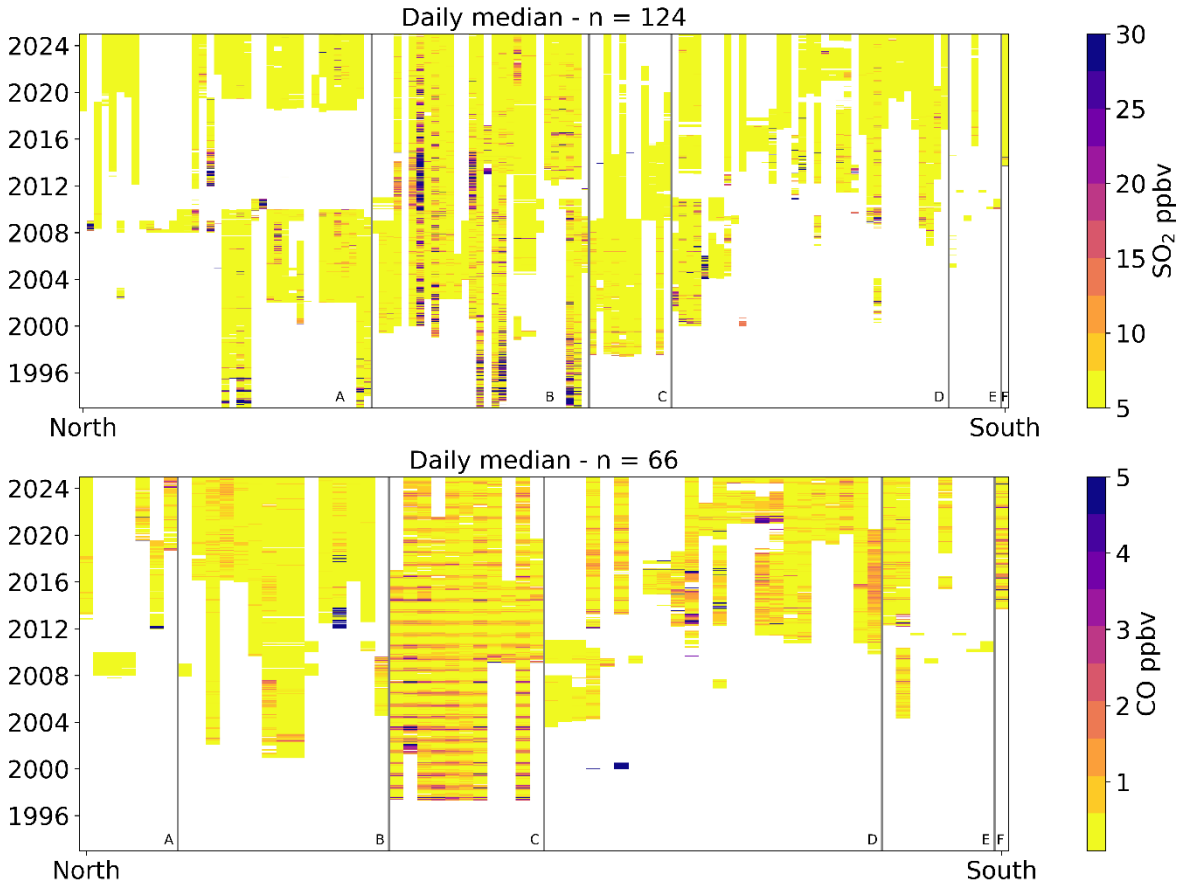


Figure S2. Daily median concentrations of SO_2 (top) and CO (bottom) from all monitoring stations with available data. The x-axis is arranged from north (left) to south (right). The number of stations used in each plot is denoted by "n" and letters from A to F indicate the macrozones from Figure 1. A: Norte Grande; B: Norte Chico; C: Santiago; D: Zona Central; D: Zona Sur; F: Zona Austral

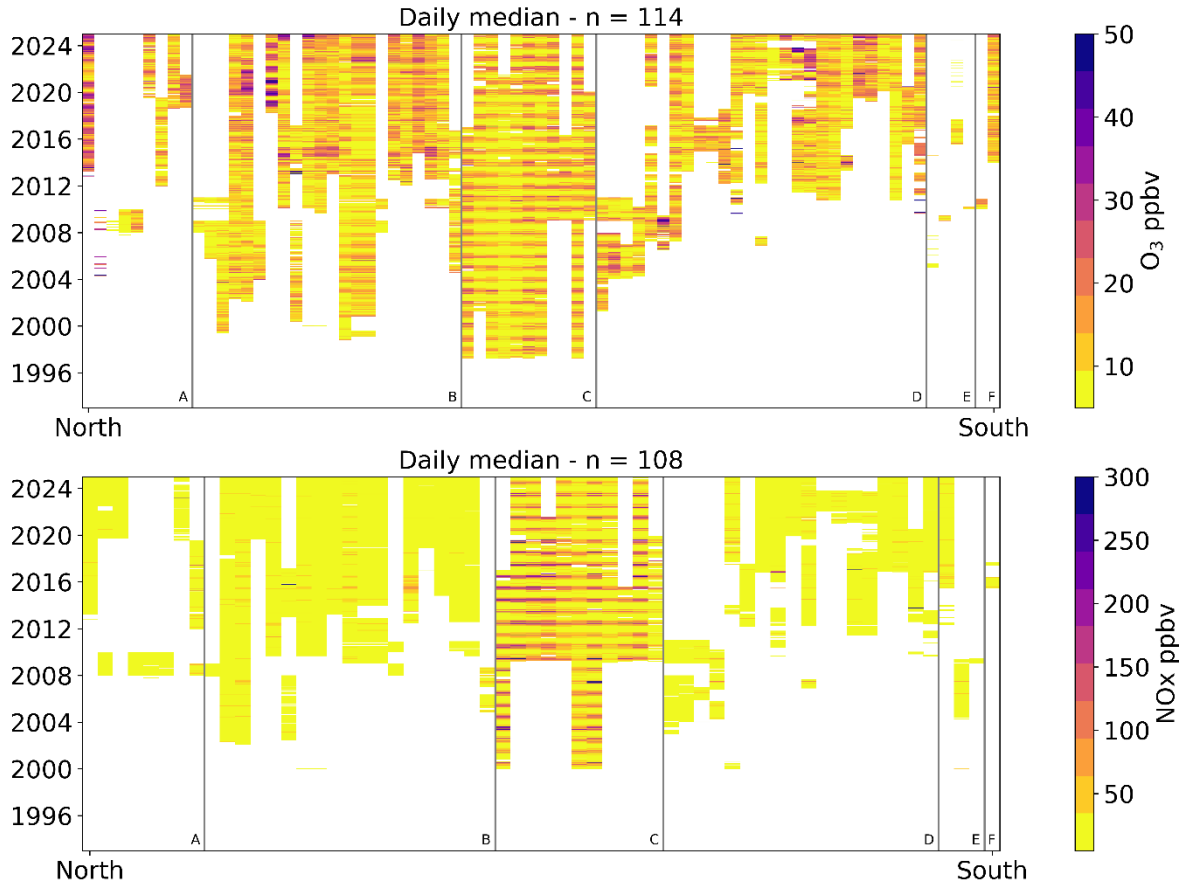


Figure S3. Daily median concentrations of O_3 (top) and NOx (bottom) from all monitoring stations with available data. The x-axis is arranged from north (left) to south (right). The number of stations used in each plot is denoted by "n" and letters from A to F indicate the macrozones from Figure 1. A: Norte Grande; B: Norte Chico; C: Santiago; D: Zona Central; D: Zona Sur; F: Zona Austral

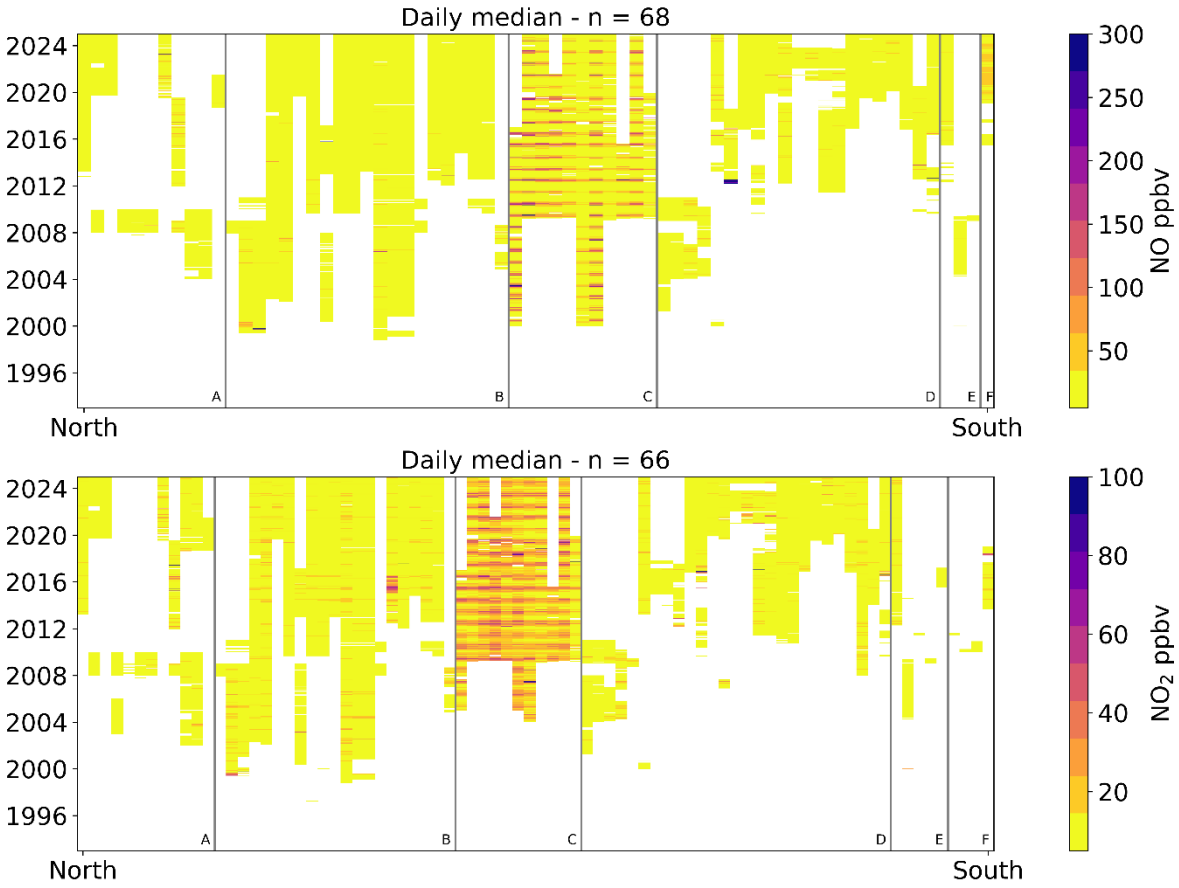


Figure S4. Daily median concentrations of NO (top) and NO_2 (bottom) from all monitoring stations with available data. The x-axis is arranged from north (left) to south (right). The number of stations used in each plot is denoted by "n" and letters from A to F indicate the macrozones from Figure 1. A: Norte Grande; B: Norte Chico; C: Santiago; D: Zona Central; D: Zona Sur; F: Zona Austral

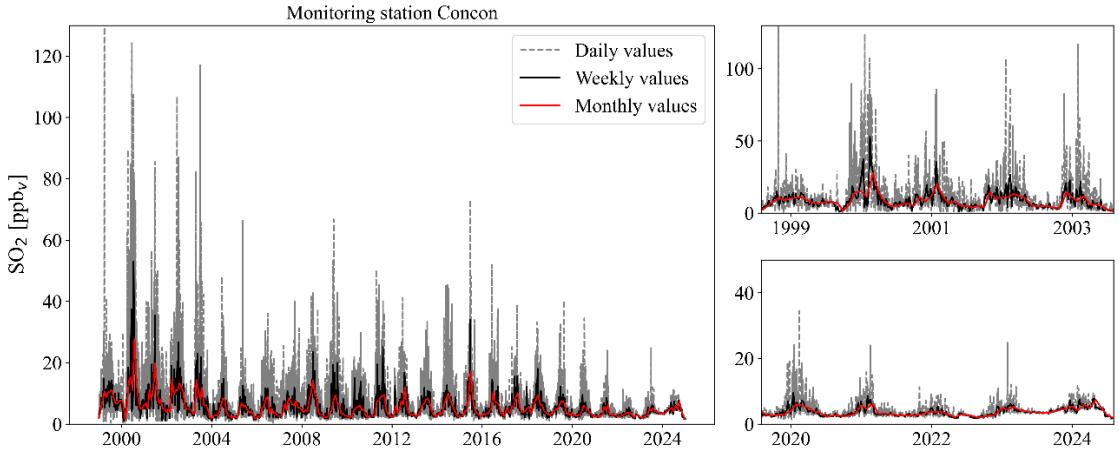


Figure S5. Long-term time series of SO_2 in ppbv at the Concon monitoring station (71.51°W, 32.92°S – Norte Chico Macrozone), illustrating daily (dotted line), weekly (solid line), and monthly (red line) median values. The main panel spans 1999 to 2024, while the inset panels on the right provides focused views of shorter intervals.

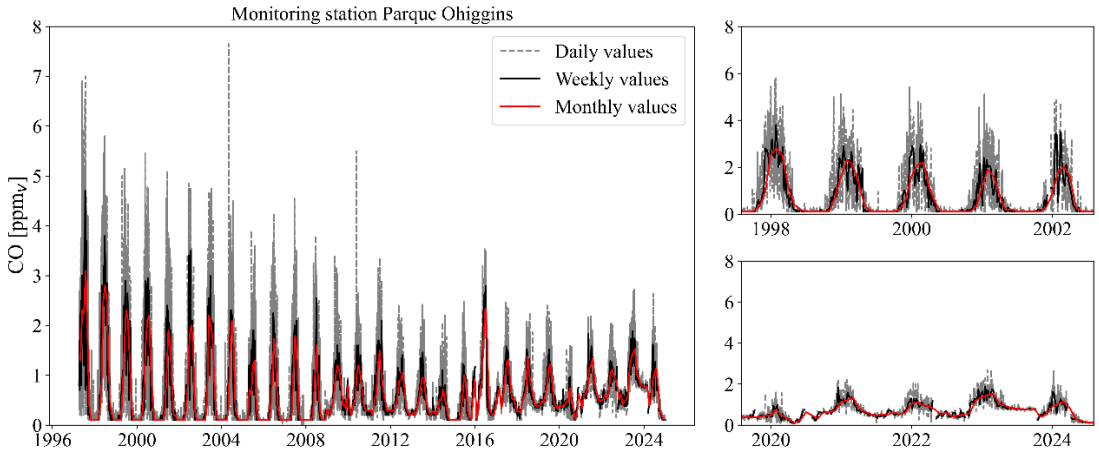


Figure S6. Long-term time series of CO in ppmv at the Parque O'Higgins monitoring station (70.67°W, 33.47°S – Zona Central Macrozone (Santiago)), illustrating daily (dotted line), weekly (solid line), and monthly (red line) median values. The main panel spans 1996 to 2024, while the inset panels on the right provides focused views of shorter intervals.

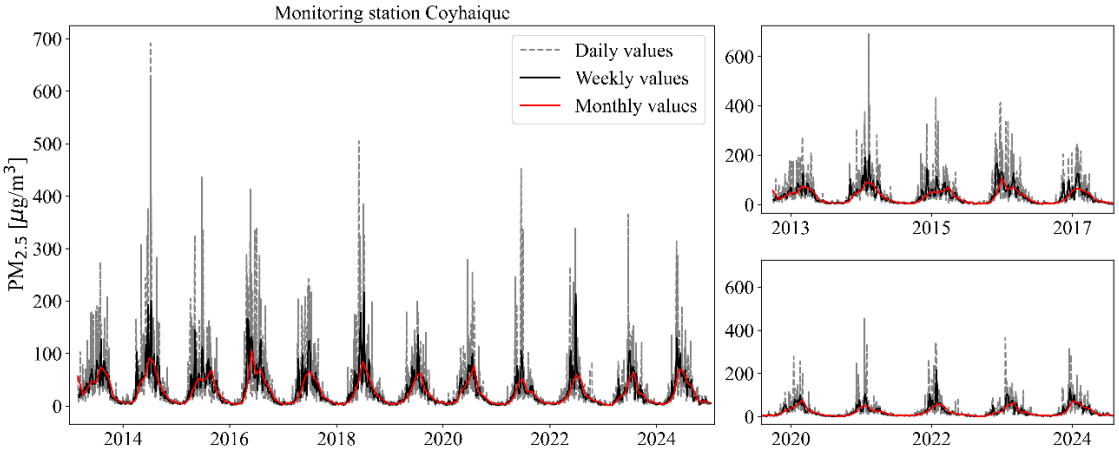


Figure S7. Long-term time series of $PM_{2.5}$ in µg/m³ at the Coyhaique monitoring station (72.06°W, 45.58°S – Zona Austral Macrozone), illustrating daily (dotted line), weekly (solid line), and monthly (red line) median values. The main panel spans 1996 to 2024, while the inset panels on the right provides focused views of shorter intervals.

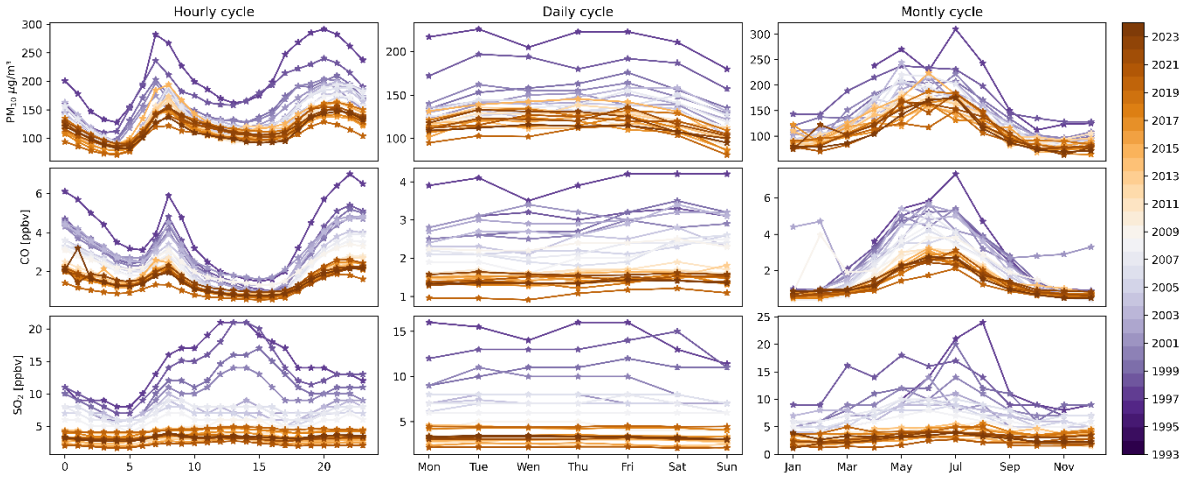


Figure S8. PM_{10} (top), CO (mid), and SO_2 (bottom) annual 90 percentiles hourly, daily and monthly concentrations for each year for the average of all monitoring stations in Santiago. This complements Figure 4 which shows $PM_{2.5}$, O_3 and NOx.

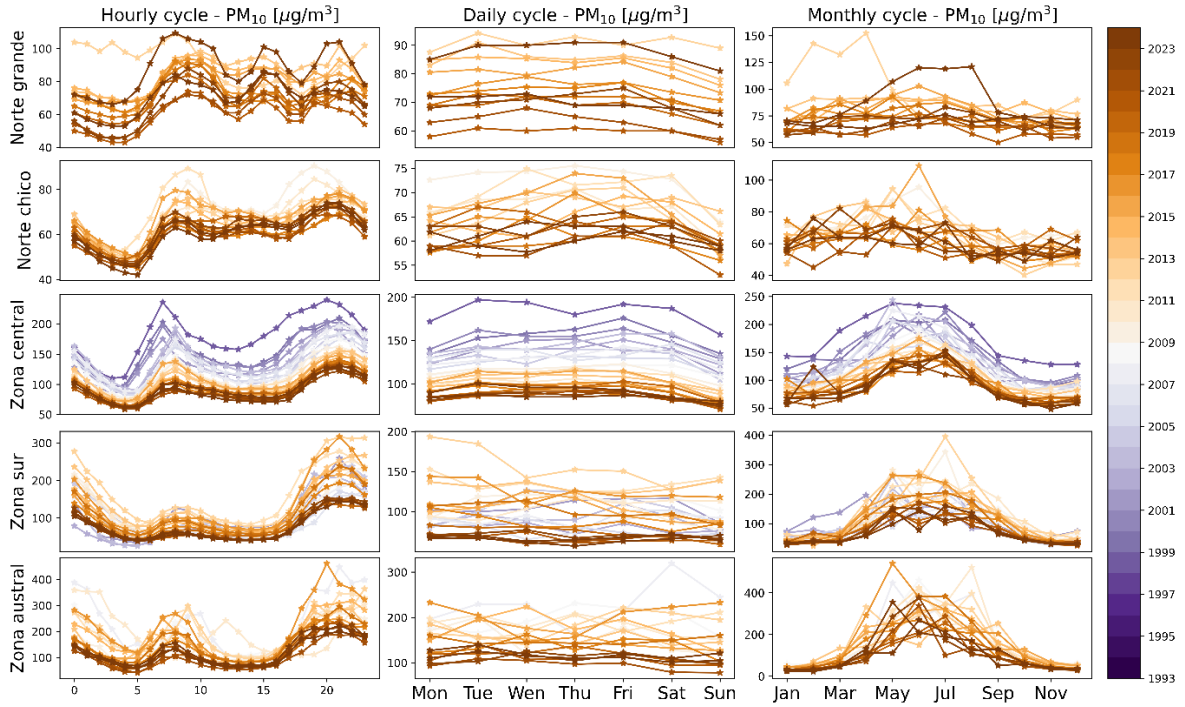


Figure S9. Hourly (left), daily (center), and monthly (right) cycles of PM_{10} concentrations in in µg/m³ for each macrozone, displayed from top (Norte Grande) to bottom (Zona Austral). Each curve corresponds to a different year, with lighter to darker shades indicating earlier to more recent data. The x-axes represent local hour of the day, day of the week, and month of the year, respectively.

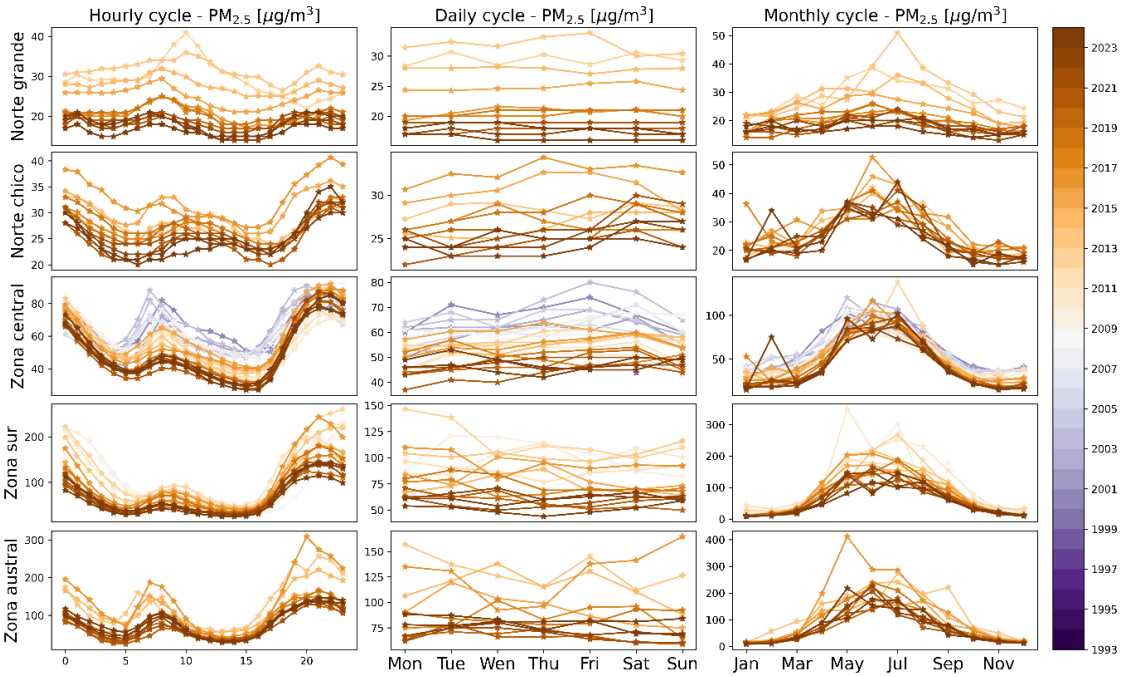


Figure S10. Hourly (left), daily (center), and monthly (right) cycles of $PM_{2.5}$ concentrations in $\mu g/m^3$ for each macrozone, displayed from top (Norte Grande) to bottom (Zona Austral). Each curve corresponds to a different year, with lighter to darker shades indicating earlier to more recent data. The x-axes represent local hour of the day, day of the week, and month of the year, respectively.

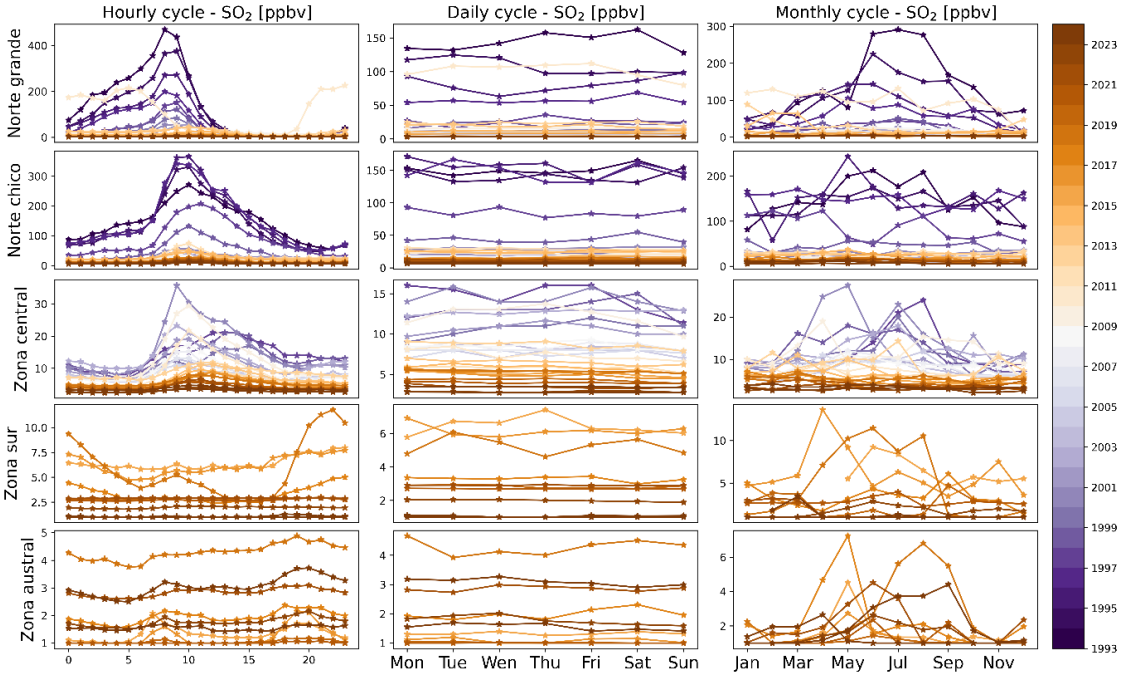


Figure S11. Hourly (left), daily (center), and monthly (right) cycles of SO_2 concentrations in ppbv for each macrozone, displayed from top (Norte Grande) to bottom (Zona Austral). Each curve corresponds to a different year, with lighter to darker shades indicating earlier to more recent data. The x-axes represent local hour of the day, day of the week, and month of the year, respectively.

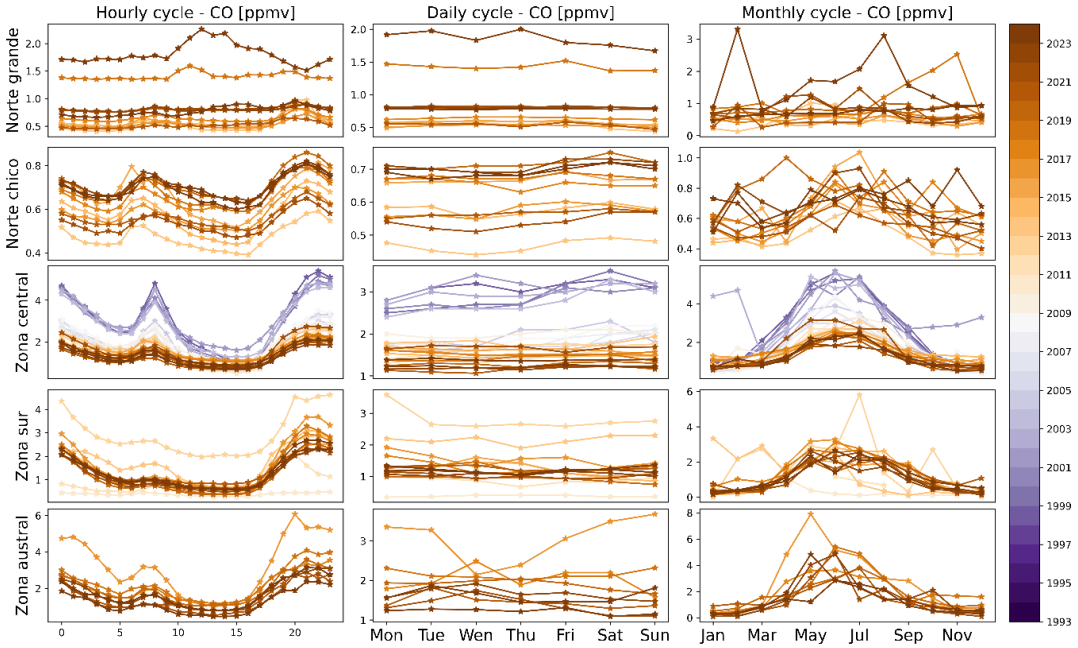


Figure S12. Hourly (left), daily (center), and monthly (right) cycles of CO concentrations in ppmv for each macrozone, arranged from Norte Grande (top) to Zona Austral (bottom). Each line represents a different year, with lighter to darker colors indicating earlier to more recent data. The x-axes show local hour of the day, day of the week, and month of the year, respectively.

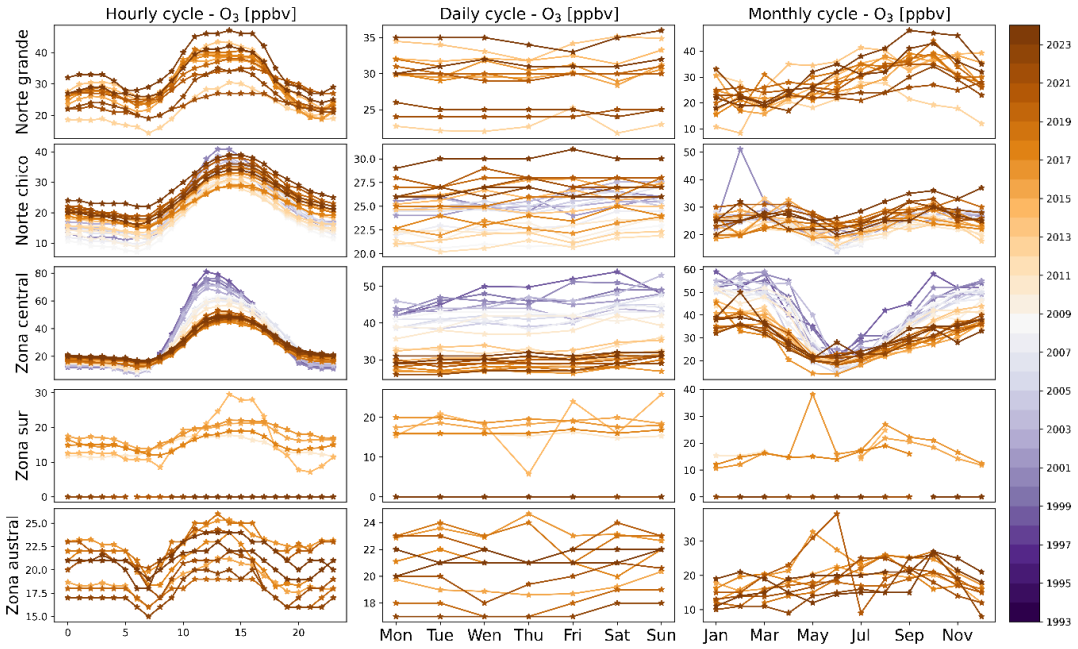


Figure S13. Hourly (left), daily (center), and monthly (right) cycles of O_3 concentrations in ppbv for each macrozone, arranged from Norte Grande (top) to Zona Austral (bottom). Each line corresponds to a different year, with lighter to darker tones representing earlier to more recent data. The x-axes denote local hour of the day, day of the week, and month of the year, respectively.

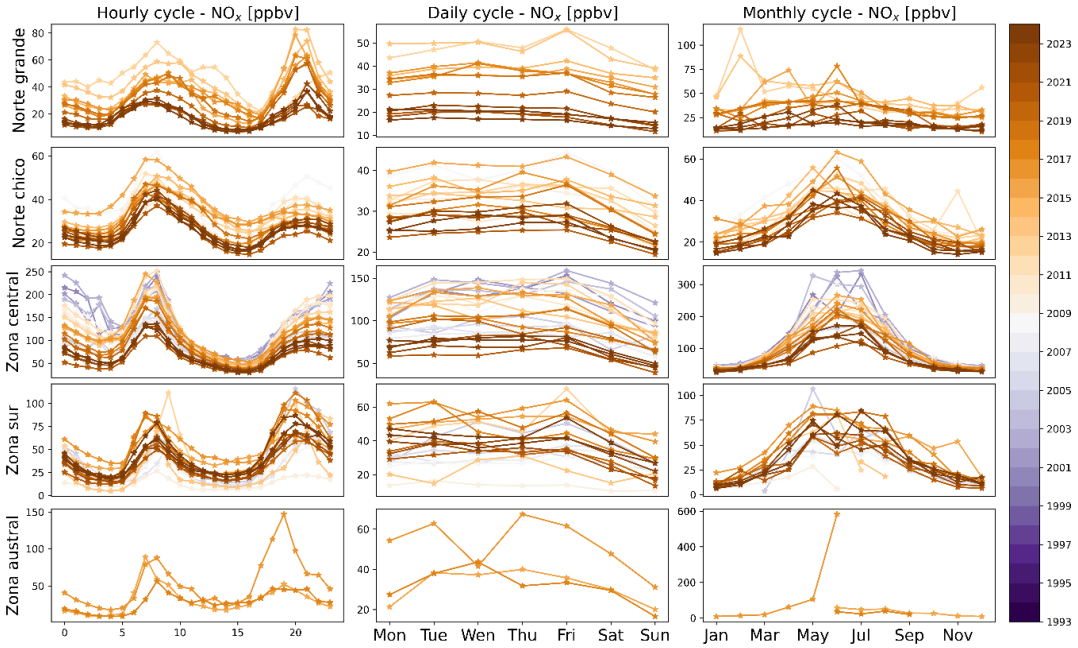


Figure S14. Hourly (left), daily (center), and monthly (right) cycles of NOx concentrations in ppbv for each macrozone, arranged from Norte Grande (top) to Zona Austral (bottom). Each line corresponds to a different year, with lighter to darker tones representing earlier to more recent data. The x-axes denote local hour of the day, day of the week, and month of the year, respectively.

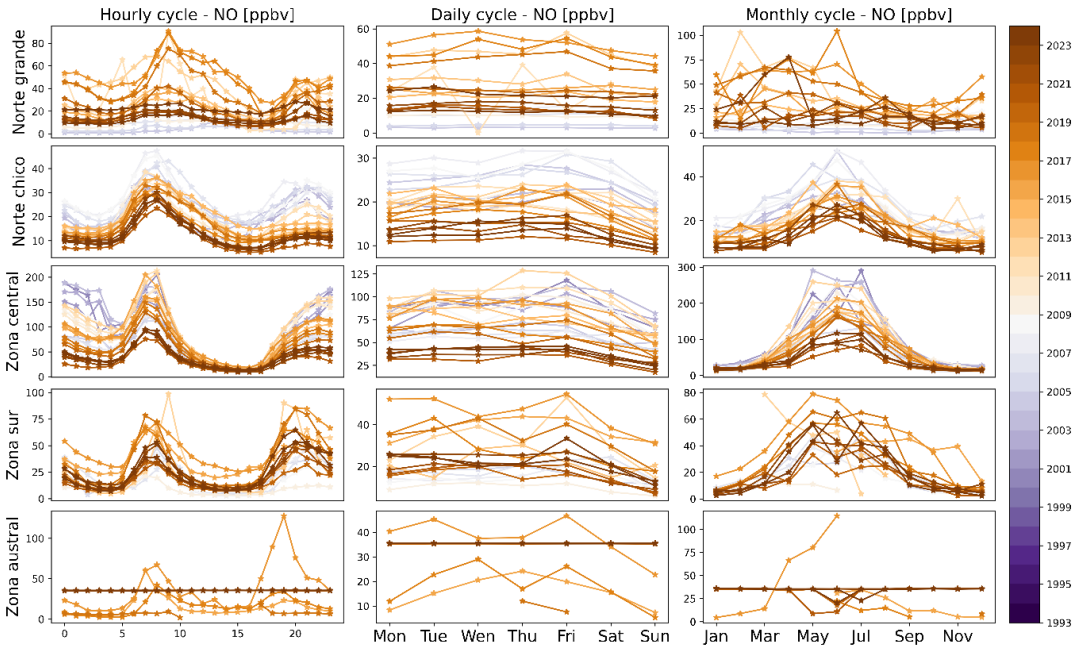


Figure S15. Hourly (left), daily (center), and monthly (right) cycles of NO concentrations in ppbv for each macrozone, arranged from Norte Grande (top) to Zona Austral (bottom). Each line corresponds to a different year, with lighter to darker tones representing earlier to more recent data. The x-axes denote local hour of the day, day of the week, and month of the year, respectively.

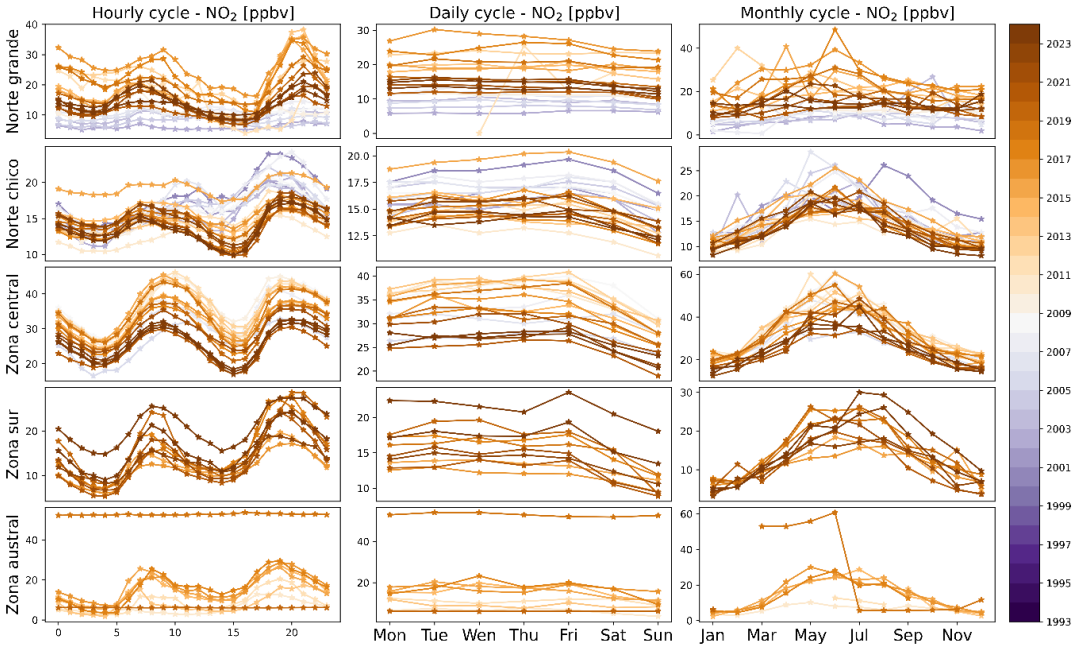


Figure S16. Hourly (left), daily (center), and monthly (right) cycles of NO_2 concentrations in ppbv for each macrozone, arranged from Norte Grande (top) to Zona Austral (bottom). Each line corresponds to a different year, with lighter to darker tones representing earlier to more recent data. The x-axes denote local hour of the day, day of the week, and month of the year, respectively.

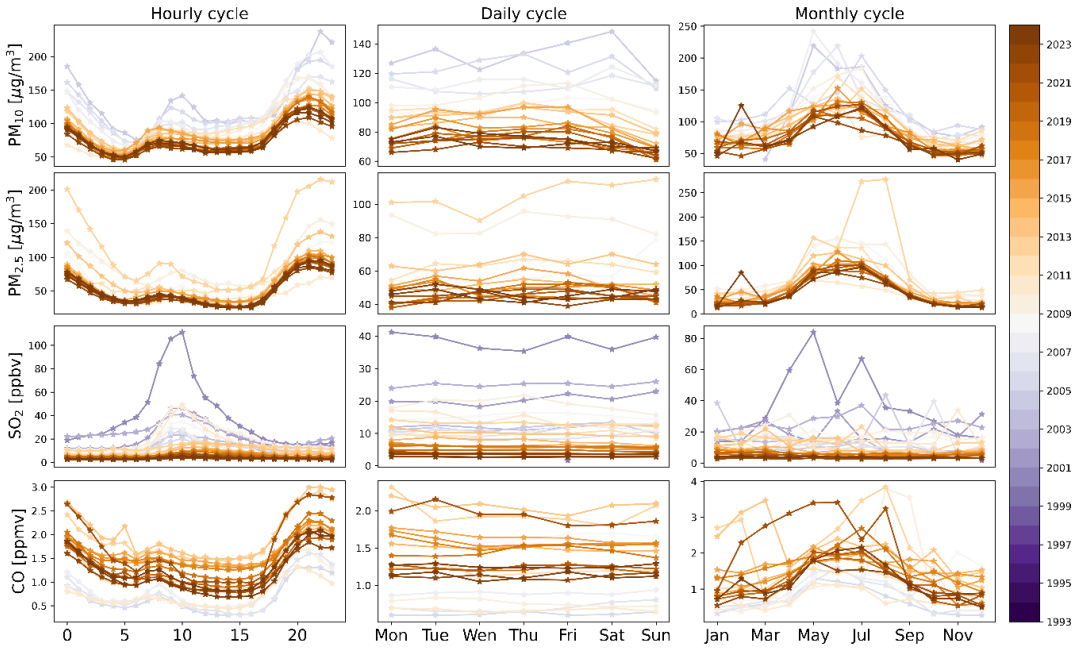


Figure S17. Hourly (left), daily (center), and monthly (right) cycles for PM_{10}, $PM_{2.5}$, SO_2 and CO concentrations in the Zona Centro macrozone, excluding Santiago. Each line represents a different year, with lighter to darker tones moving from earlier to more recent data. The x-axes indicate local hour of the day, day of the week, and month of the year, respectively.

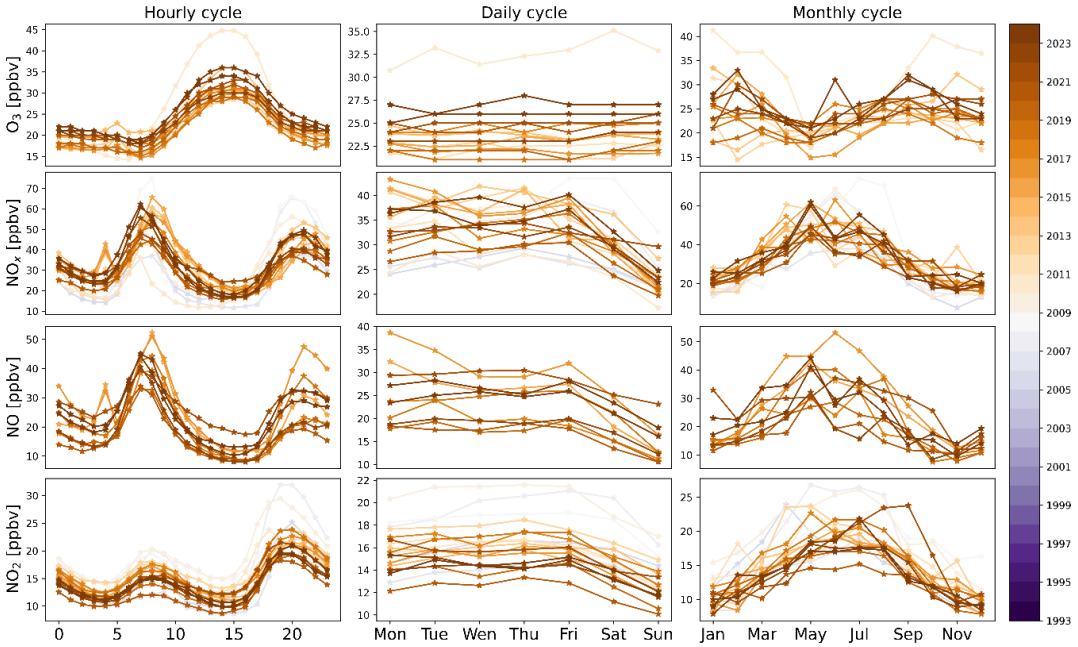


Figure S18. Hourly (left), daily (center), and monthly (right) cycles of O_3, NO_x, NO, and NO_2 concentration for the Zona Centro macrozone, excluding data from Santiago. Each line represents a different year, with lighter to darker tones indicating earlier to more recent measurements. The x-axes show local hour of the day, day of the week, and month of the year, respectively.

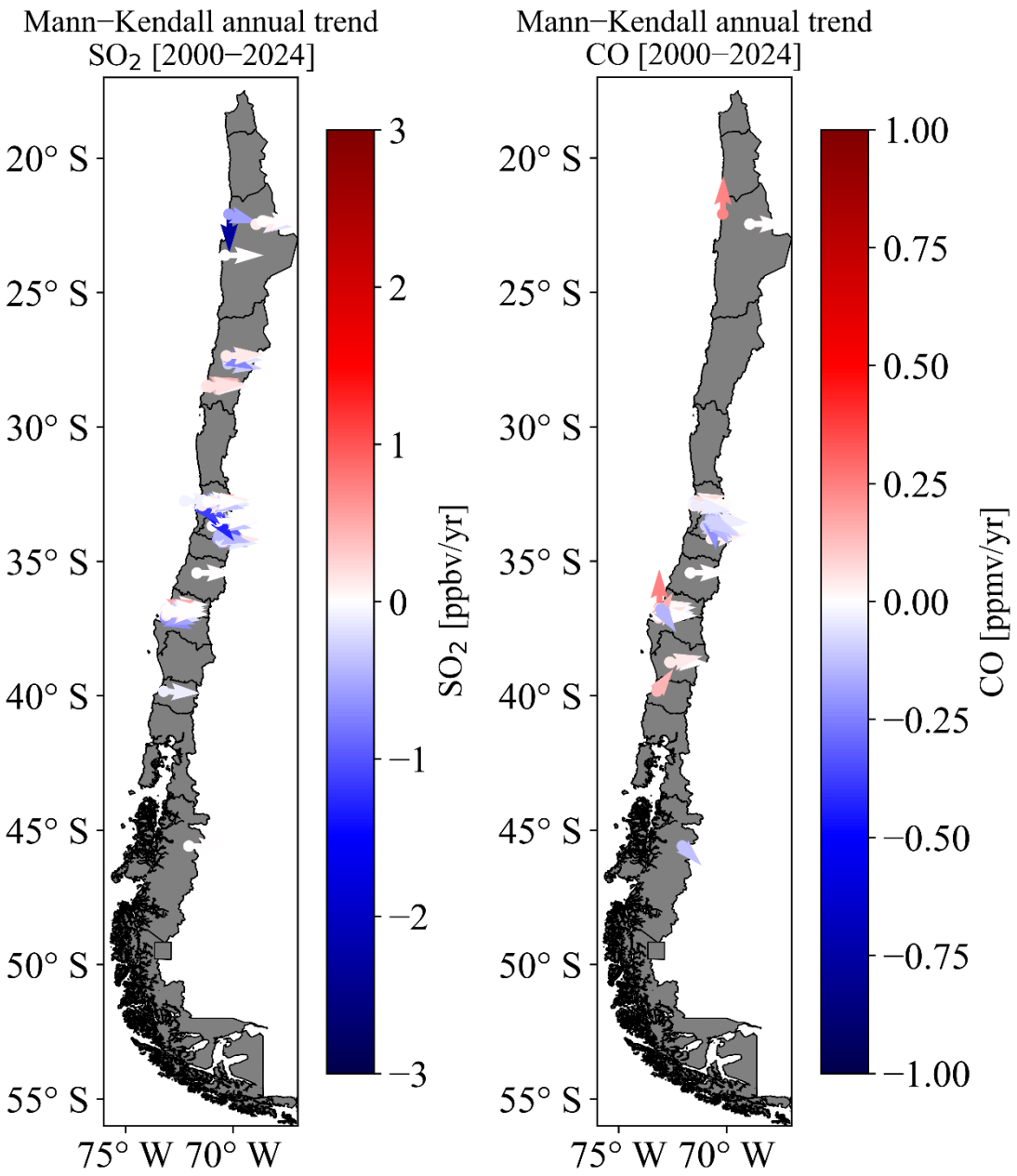


Figure S19. Trend analysis of SO_2 (ppbv yr^{-1}) and CO (ppm yr^{-1}) mixing ratios from 2000 to 2024, based on the Mann-Kendall test. The colour scale represents the magnitude of change in mixing ratio per year, with red indicating increases and blue indicating decreases. Arrows show the direction and rate of the observed trends.

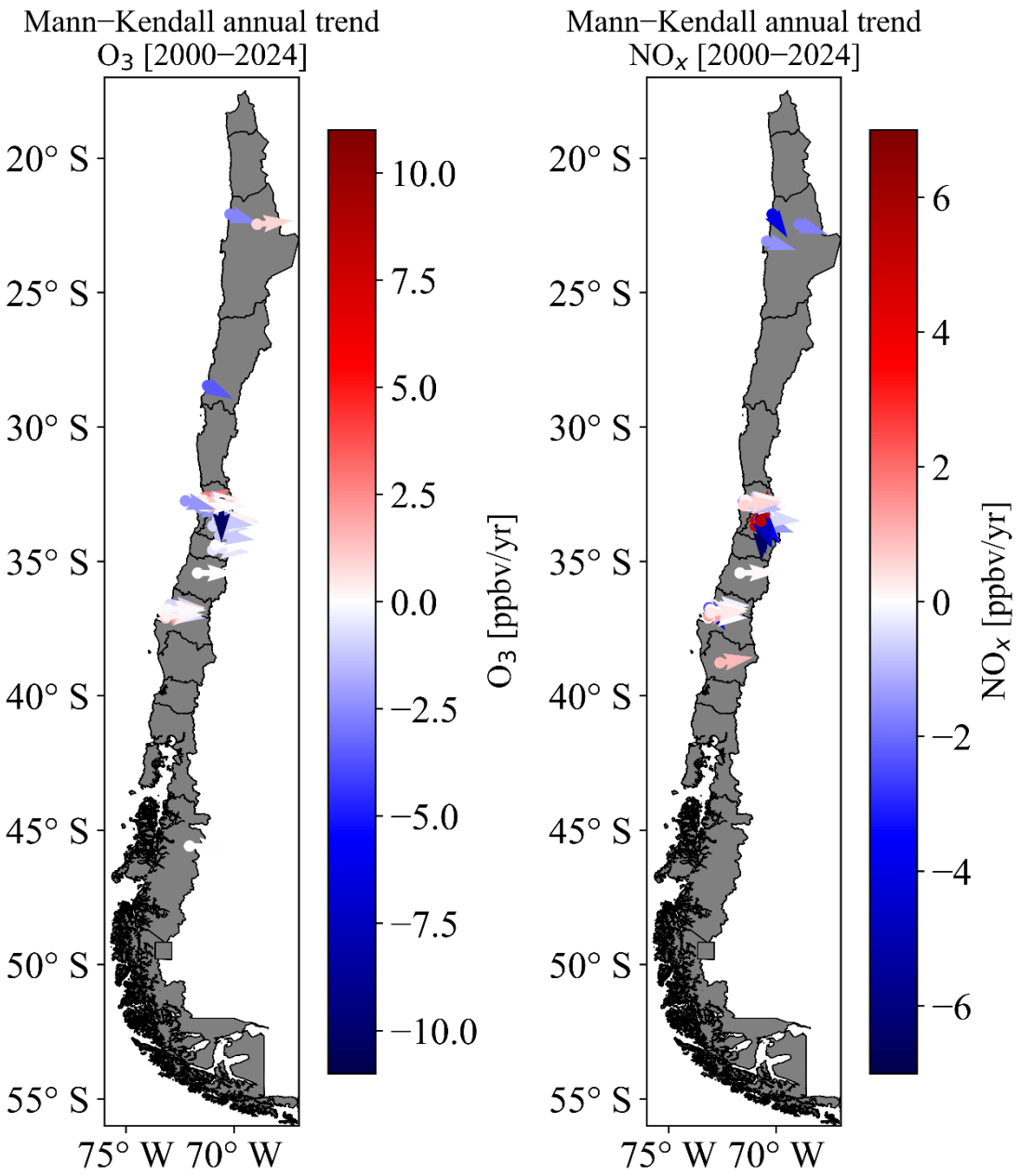


Figure S20. Trend analysis of O_3 (ppbv yr^{-1}) and NOx (ppbv yr^{-1}) mixing ratios from 2000 to 2024, based on the Mann-Kendall test. The colour scale represents the magnitude of change in mixing ratio per year, with red indicating increases and blue indicating decreases. Arrows show the direction and rate of the observed trends

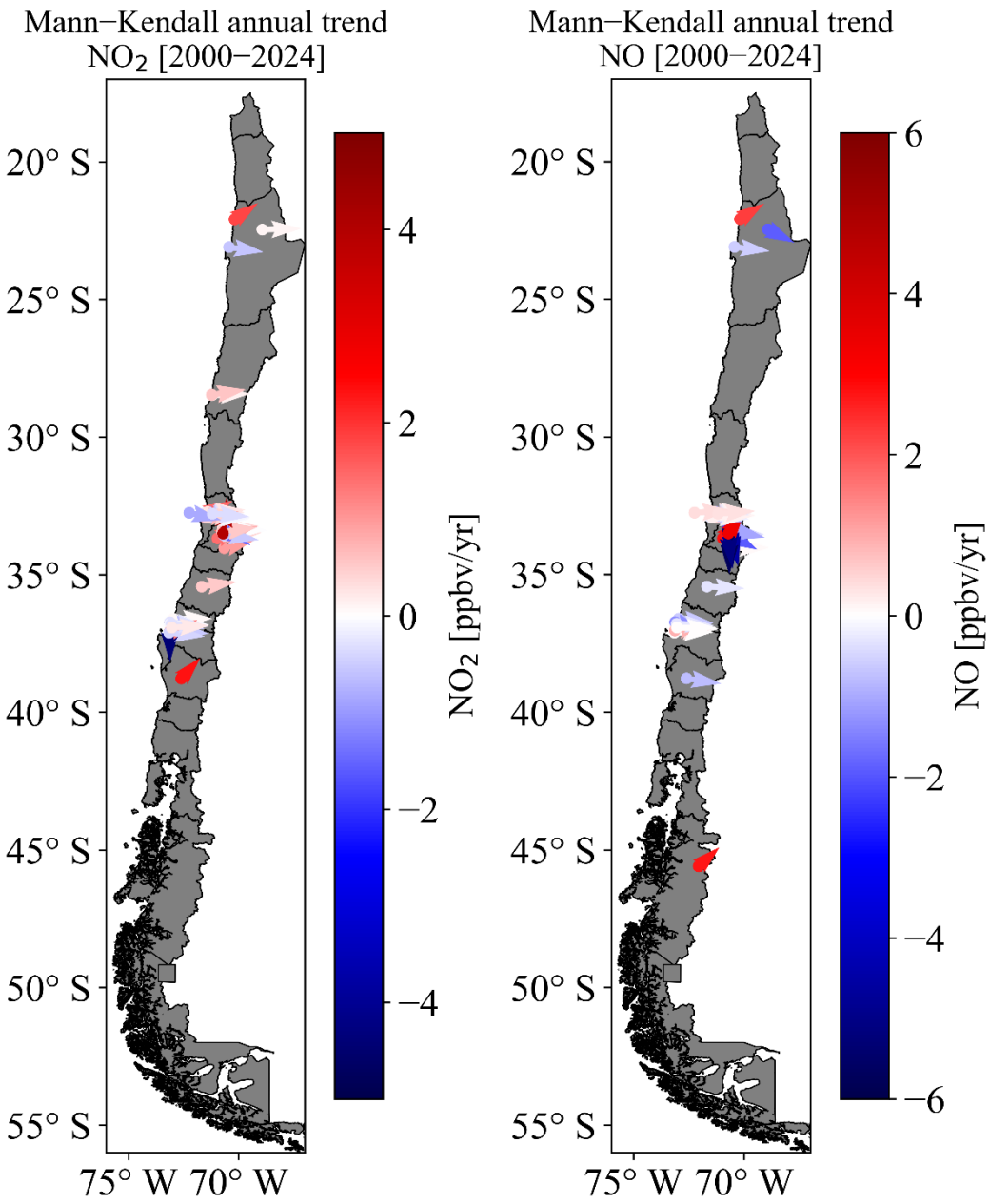


Figure S21. Trend analysis of NO_2 (ppbv yr^{-1}) and NO (ppbv yr^{-1}) mixing ratios from 2000 to 2024, based on the Mann-Kendall test. The colour scale represents the magnitude of change in mixing ratio per year, with red indicating increases and blue indicating decreases. Arrows show the direction and rate of the observed trends

Section S4- Individual Station trends

Table S3. National trend analysis for PM_{10} concentrations (2000–2024) across Chile, organized by macrozone. The table displays the trend direction, the estimated slope (μg m^{-3} yr^{-1}), and the corresponding p-value for each monitoring station.

Macrozone	2000-2024	Trend	PM_{10} ug m^{-3} yr^{-1}	P-value
Norte grande	Antofagasta	decreasing	-2.65	0.00
Norte grande	Club Deportivo 23 de Marzo	decreasing	-1.20	0.00
Norte grande	Colegio Pedro Vergara Keller	decreasing	-2.95	0.00
Norte grande	Estación Centro	decreasing	-5.55	0.00
Norte grande	Sierra Gorda	increasing	17.48	0.00
Norte grande	Gobernacion	decreasing	-7.64	0.00
Norte grande	Tres Marias	decreasing	-9.30	0.00
Norte grande	Escuela E-10	decreasing	-11.70	0.00
Norte grande	Copiapo Sivica	decreasing	-3.99	0.00
Norte chico	Andacollo	decreasing	-3.57	0.00
Norte chico	Cuncumen	increasing	2.10	0.00
Norte chico	Concon	decreasing	-3.16	0.00
Norte chico	Puchuncavi	increasing	1.76	0.00
Norte chico	La Greda	decreasing	-0.71	0.00
Norte chico	Los Maitenes	decreasing	-0.98	0.00
Norte chico	Ventanas	decreasing	-4.61	0.00
Norte chico	Cuerpo de Bomberos	no trend	-0.36	0.23
Norte chico	La Palma	no trend	-0.44	0.13
Norte chico	San Pedro	no trend	-0.44	0.13
Norte chico	Loncura	decreasing	-0.87	0.00
Norte chico	Quintero	decreasing	-5.99	0.00
Norte chico	Sur	decreasing	-1.45	0.00
Norte chico	Valle Alegre	decreasing	-2.37	0.00
Norte chico	Viña del Mar	decreasing	-1.54	0.00
Zona centro	Cerrillos I	no trend	0.00	0.99
Zona centro	Cerro Navia	no trend	0.87	0.08
Zona centro	El Bosque	no trend	0.00	0.76
Zona centro	Independencia	decreasing	-1.19	0.00
Zona centro	La Florida	decreasing	-2.01	0.00
Zona centro	Las Condes	no trend	0.38	0.05
Zona centro	Pudahuel	no trend	0.51	0.24
Zona centro	Puente Alto	increasing	2.14	0.00
Zona centro	Quilicura	no trend	1.33	0.44
Zona centro	Quilicura I	increasing	5.34	0.05
Zona centro	Parque Ohiggins	decreasing	-0.76	0.05
Zona centro	Talagante	increasing	2.85	0.00
Zona centro	Rancagua I	no trend	-0.43	0.32
Zona centro	Rancagua II	decreasing	-14.44	0.00
Zona centro	Rengo	no trend	0.38	0.27
Zona centro	San Fernando	increasing	0.73	0.02
Zona centro	Curico	decreasing	-2.54	0.00
Zona centro	La Florida Talca	decreasing	-5.53	0.00
Zona centro	UC Maule	decreasing	-1.64	0.00
Zona centro	Universidad de Talca	decreasing	-1.67	0.00
Zona sur	INIA Chillan	decreasing	-1.92	0.00
Zona sur	Puren	decreasing	-3.26	0.00
Zona sur	Colicheu	no trend	-0.29	0.28
Zona sur	Punteras	no trend	0.07	0.38
Zona sur	Kingstone College	decreasing	-1.01	0.00
Zona sur	Cerro Merquin	no trend	0.10	0.47
Zona sur	Coronel Sur	no trend	-0.14	0.65
Zona sur	Lota rural	decreasing	-4.76	0.00
Zona sur	Lota urbana	increasing	2.89	0.00
Zona sur	Bocatoma	decreasing	-1.01	0.00
Zona sur	ENAP Price	decreasing	-1.12	0.00

Macrozone	2000-2024	Trend	PM_{10} ug m^{-3} yr^{-1}	P-value
Zona sur	JUNJI	no trend	0.24	0.41
Zona sur	Hualqui	no trend	0.72	0.21
Zona sur	21 de mayo	decreasing	-3.99	0.00
Zona sur	Los Angeles Oriente	decreasing	-0.73	0.05
Zona sur	Consultorio San Vicente	decreasing	-3.24	0.00
Zona sur	Indura	decreasing	-1.57	0.00
Zona sur	Inpesca	decreasing	-1.11	0.00
Zona sur	Nueva Libertad	no trend	0.39	0.33
Zona sur	Liceo Polivalente	increasing	0.63	0.00
Zona sur	Padre Las Casas II	decreasing	-4.59	0.00
Zona sur	Padre Las Casas	no trend	0.08	0.90
Zona sur	Las Encinas Temuco	no trend	0.30	0.09
Zona sur	Nielol	no trend	-0.74	0.32
Zona sur	Museo Ferroviario	no trend	-1.45	0.29
Zona sur	Valdivia	no trend	-0.30	0.17
Zona sur	Osorno	no trend	0.00	0.92
Zona austral	Coyhaique	decreasing	-5.09	0.00
Zona austral	Coyhaique II	decreasing	-14.40	0.00

Table S4. National trend analysis for $PM_{2.5}$ concentrations (2000–2024) across Chile, organized by macrozone. The table displays the trend direction, the estimated slope (μg m^{-3} yr^{-1}), and the corresponding p-value for each monitoring station.

Macrozone	2000-2024	Trend	$PM_{2.5}$ ug m^{-3} yr^{-1}	P-value
Norte grande	Arica	decreasing	-1.39	0.00
Norte grande	Alto Hospicio	decreasing	-1.44	0.00
Norte grande	Antofagasta	decreasing	-0.70	0.00
Norte grande	Club Deportivo 23 de Marzo	decreasing	-0.01	0.00
Norte grande	Colegio Pedro Vergara Keller	decreasing	-0.47	0.00
Norte grande	Estación Centro	decreasing	-0.92	0.00
Norte grande	Sierra Gorda	increasing	0.00	0.04
Norte grande	Bomberos	decreasing	-3.29	0.00
Norte grande	Tres Marias	decreasing	-5.16	0.00
Norte grande	Escuela E-10	decreasing	-3.58	0.00
Norte grande	Copiapo Sivica	decreasing	-4.00	0.00
Norte grande	Huasco Sivica	decreasing	-2.09	0.00
Norte chico	Coquimbo	decreasing	-1.60	0.00
Norte chico	La Serena	decreasing	-1.44	0.00
Norte chico	Concon MMA	decreasing	-3.92	0.00
Norte chico	Concon	decreasing	-2.78	0.00
Norte chico	Puchuncavi	decreasing	-1.42	0.00
Norte chico	La Greda	decreasing	-0.80	0.00
Norte chico	Los Maitenes	decreasing	-1.22	0.00
Norte chico	Ventanas	decreasing	-1.76	0.00
Norte chico	Loncura	decreasing	-1.63	0.00
Norte chico	Quintero	decreasing	-3.57	0.00
Norte chico	Valparaiso	decreasing	-2.12	0.00
Norte chico	Vina del Mar	decreasing	-1.12	0.00
Zona centro	Cerrillos I	increasing	4.64	0.00
Zona centro	Cerro Navia	no trend	-0.71	0.07
Zona centro	El Bosque	increasing	0.61	0.02
Zona centro	Independencia	no trend	0.00	0.45
Zona centro	La Florida	decreasing	-1.84	0.00
Zona centro	Las Condes	decreasing	-1.10	0.00
Zona centro	Pudahuel	no trend	-0.31	0.14
Zona centro	Puente Alto	decreasing	-0.78	0.00
Zona centro	Quilicura	no trend	-0.83	0.20
Zona centro	Quilicura I	increasing	3.58	0.00
Zona centro	Parque Ohiggins	decreasing	-3.03	0.00
Zona centro	Talagante	increasing	1.27	0.00
Zona centro	Rancagua I	decreasing	-2.41	0.00
Zona centro	Rancagua II	decreasing	-3.70	0.00
Zona centro	Rengo	no trend	0.00	0.59
Zona centro	San Fernando	no trend	0.00	0.53
Zona centro	Curico	decreasing	-1.24	0.00
Zona centro	Linares	decreasing	-5.43	0.00
Zona centro	La Florida Talca	decreasing	-2.09	0.00
Zona centro	UC Maule	decreasing	-1.08	0.00
Zona centro	Universidad de Talca	decreasing	-0.99	0.00
Zona sur	INIA Chillan	decreasing	-1.80	0.00
Zona sur	Puren	decreasing	-2.00	0.00
Zona sur	Punteras	increasing	1.37	0.00
Zona sur	Kingstone College	decreasing	-1.05	0.00
Zona sur	Cerro Merquin	decreasing	0.00	0.59
Zona sur	Balneario Curanilahue	decreasing	6.47	0.00
Zona sur	ENAP Price	no trend	-2.41	0.03
Zona sur	JUNJI	no trend	0.00	0.83
Zona sur	Hualqui	increasing	2.47	0.00
Zona sur	21 de mayo	decreasing	2.11	0.00
Zona sur	Los Angeles Oriente	decreasing	-1.89	0.00
Zona sur	Consultorio San Vicente	no trend	-2.20	0.00

Macrozone	2000-2024	Trend	$PM_{2.5}$ ug m^{-3} yr^{-1}	P-value
Zona sur	Indura	no trend	0.00	0.83
Zona sur	Inpesca	decreasing	0.47	0.14
Zona sur	Nueva Libertad	increasing	-0.48	0.14
Zona sur	Liceo Polivalente	decreasing	0.88	0.00
Zona sur	Padre Las Casas II	decreasing	0.00	0.49
Zona sur	Las Encinas Temuco	decreasing	-2.10	0.00
Zona sur	Nielol	no trend	-2.30	0.00
Zona sur	Museo Ferroviario	no trend	0.00	1.00
Zona sur	Valdivia	decreasing	-0.51	0.61
Zona sur	Osorno	decreasing	-0.88	0.24
Zona sur	Alerce	no trend	-1.96	0.00
Zona sur	Mirasol	decreasing	-1.43	0.00
Zona austral	Coyhaique	decreasing	0.00	0.63
Zona austral	Coyhaique II	decreasing	-2.44	0.00
Zona austral	Punta Arenas	decreasing	-2.68	0.00

Table S5. National trend analysis for SO_2 concentrations (2000–2024) across Chile, organized by macrozone. The table displays the trend direction, the estimated slope (**ppbv yr^{-1}**), and the corresponding p-value for each monitoring station.

Macrozone	2000-2024	Trend	SO_2 ppbv yr^{-1}	P-value
Norte grande	Antofagasta	decreasing	0.00	0.00
Norte grande	Chiu Chiu	no trend	0.01	0.10
Norte grande	Estación Centro	increasing	0.10	0.00
Norte grande	Hospital el Cobre	decreasing	-0.17	0.00
Norte grande	Oasis	increasing	0.12	0.00
Norte grande	Gobernacion	decreasing	-0.54	0.00
Norte grande	Escuela E-10	decreasing	-2.33	0.00
Norte grande	Copiapo	increasing	0.13	0.00
Norte grande	Los Volcanes	increasing	0.07	0.00
Norte grande	Paipote	decreasing	-0.73	0.00
Norte grande	San Fernando Atacama	decreasing	-0.19	0.00
Norte grande	SM6	increasing	0.17	0.00
Norte grande	SM7	increasing	0.22	0.00
Norte grande	SM8	increasing	0.08	0.00
Norte grande	EME F	increasing	0.14	0.00
Norte grande	EME M	no trend	0.01	0.23
Norte grande	SM1	increasing	0.13	0.00
Norte grande	SM2	increasing	0.44	0.00
Norte grande	SM3	increasing	0.36	0.00
Norte grande	SM4	increasing	0.15	0.00
Norte grande	SM5	decreasing	-0.09	0.00
Norte grande	Tierra Amarilla	no trend	0.00	0.39
Norte grande	Pabellon	decreasing	-0.29	0.00
Norte chico	La Calera	no trend	0.00	0.78
Norte chico	Rural 1	decreasing	-0.08	0.00
Norte chico	Catemu	increasing	0.11	0.00
Norte chico	Romeral	decreasing	-0.34	0.00
Norte chico	Santa Margarita	decreasing	-0.11	0.00
Norte chico	Colmo	increasing	0.12	0.00
Norte chico	Concon	decreasing	-1.14	0.00
Norte chico	Junta de Vecinos	decreasing	-0.08	0.00
Norte chico	Las Gaviotas	decreasing	-0.06	0.00
Norte chico	Lo Campo	decreasing	-0.19	0.00
Norte chico	Puchuncavi	increasing	0.03	0.02
Norte chico	La Greda	decreasing	-0.15	0.00
Norte chico	Los Maitenes	decreasing	-0.41	0.00
Norte chico	Ventanas	decreasing	-0.93	0.00
Norte chico	Cuerpo de Bomberos	increasing	0.62	0.00
Norte chico	La Palma	decreasing	-0.06	0.00
Norte chico	San Pedro	decreasing	-0.06	0.00
Norte chico	Centro Quintero	decreasing	-1.01	0.00
Norte chico	Loncura	decreasing	-1.42	0.00
Norte chico	Quintero	decreasing	-1.40	0.00
Norte chico	Sur	decreasing	-0.28	0.00
Norte chico	Valle Alegre	decreasing	-0.03	0.01
Zona centro	Cerrillos I	increasing	0.00	0.00
Zona centro	Cerro Navia	decreasing	-1.30	0.00
Zona centro	El Bosque	decreasing	-0.34	0.00
Zona centro	Independencia	decreasing	-0.94	0.00
Zona centro	La Florida	decreasing	-0.04	0.00
Zona centro	Las Condes	decreasing	0.00	0.00
Zona centro	Pudahuel	increasing	0.00	0.00
Zona centro	Puente Alto	increasing	0.11	0.00
Zona centro	Parque Ohiggins	decreasing	-0.97	0.00
Zona centro	Talagante	no trend	0.00	0.10
Zona centro	Codegua	decreasing	-0.42	0.00
Zona centro	Cauquenes	decreasing	-0.14	0.00

Macrozone	2000-2024	Trend	SO_2 ppbv yr^{-1}	P-value
Zona centro	Cipreses	increasing	0.15	0.00
Zona centro	Coya Poblacion	no trend	-0.01	0.11
Zona centro	Rancagua I	decreasing	-0.50	0.00
Zona centro	La Florida Talca	increasing	0.00	0.00
Zona sur	Punteras	increasing	0.00	0.00
Zona sur	Kingstone College	decreasing	0.00	0.00
Zona sur	Calabozo	increasing	0.12	0.00
Zona sur	Coronel Sur	decreasing	-0.52	0.00
Zona sur	Lota rural	decreasing	-0.68	0.00
Zona sur	Lota urbana	decreasing	-0.17	0.00
Zona sur	Bocatoma	decreasing	-0.06	0.00
Zona sur	ENAP Price	decreasing	-0.16	0.00
Zona sur	JUNJI	decreasing	-0.34	0.00
Zona sur	Hualqui	decreasing	0.00	0.00
Zona sur	Consultorio San Vicente	increasing	0.01	0.00
Zona sur	Indura	decreasing	-0.27	0.00
Zona sur	Inpesca	decreasing	-0.28	0.00
Zona sur	Nueva Libertad	increasing	0.50	0.00
Zona sur	Liceo Polivalente	increasing	0.00	0.00
Zona sur	Valdivia	decreasing	-0.11	0.00
Zona austral	Coyhaique II	decreasing	0.00	0.00

Table S6. National trend analysis for CO concentrations (2000–2024) across Chile, organized by macrozone. The table displays the trend direction, the estimated slope (**ppmv yr^{-1}**), and the corresponding p-value for each monitoring station.

Macrozone	**2000-2024**	**Trend**	**CO ppmv yr^{-1}**	**P-value**
Norte grande	Estación Centro	no trend	0.00	0.73
Norte grande	Escuela E-10	increasing	0.24	0.00
Norte chico	Colmo	decreasing	-0.03	0.00
Norte chico	Concon	increasing	0.01	0.00
Norte chico	Junta de Vecinos	increasing	0.07	0.00
Norte chico	Las Gaviotas	no trend	-0.01	0.07
Norte chico	Los Maitenes	decreasing	-0.04	0.00
Norte chico	Cuerpo de Bomberos	decreasing	-0.05	0.00
Norte chico	La Palma	increasing	0.01	0.00
Norte chico	San Pedro	increasing	0.01	0.00
Norte chico	Centro Quintero	decreasing	-0.01	0.03
Norte chico	Loncura	increasing	0.04	0.00
Norte chico	Quintero	no trend	0.00	0.23
Norte chico	Sur	decreasing	-0.02	0.00
Zona centro	Cerrillos I	decreasing	-0.09	0.00
Zona centro	Cerro Navia	decreasing	-0.14	0.00
Zona centro	El Bosque	decreasing	-0.07	0.00
Zona centro	Independencia	decreasing	-0.12	0.00
Zona centro	La Florida	decreasing	-0.15	0.00
Zona centro	Las Condes	decreasing	-0.03	0.00
Zona centro	Pudahuel	decreasing	-0.04	0.00
Zona centro	Puente Alto	decreasing	-0.08	0.00
Zona centro	Quilicura I	decreasing	-0.21	0.00
Zona centro	Parque Ohiggins	decreasing	-0.12	0.00
Zona centro	Talagante	decreasing	-0.09	0.00
Zona centro	Rancagua I	increasing	0.03	0.00
Zona centro	La Florida Talca	no trend	0.00	0.73
Zona sur	Kingstone College	decreasing	-0.15	0.00
Zona sur	Coronel Sur	no trend	0.00	0.81
Zona sur	Lota rural	increasing	0.07	0.00
Zona sur	Lota urbana	increasing	0.15	0.00
Zona sur	ENAP Price	increasing	0.01	0.01
Zona sur	JUNJI	decreasing	-0.02	0.00
Zona sur	Indura	increasing	0.04	0.00
Zona sur	Nueva Libertad	increasing	0.24	0.00
Zona sur	Padre Las Casas II	increasing	0.04	0.00
Zona sur	Las Encinas Temuco	decreasing	0.00	0.03
Zona sur	Valdivia	increasing	0.14	0.00
Zona austral	Coyhaique II	decreasing	-0.12	0.00

Table S7. National trend analysis for O_3 concentrations (2000–2024) across Chile, organized by macrozone. The table displays the trend direction, the estimated slope (**ppbv yr^{-1}**), and the corresponding p-value for each monitoring station.

Macrozone	**2000-2024**	**Trend**	**O_3 ppbv yr^{-1}**	**P-value**
Norte grande	Estación Centro	increasing	0.94	0.00
Norte grande	Escuela E-10	decreasing	-2.63	0.00
Norte grande	EME F	decreasing	-3.53	0.00
Norte chico	Rural 1	decreasing	-2.29	0.00
Norte chico	Colmo	no trend	0.00	0.87
Norte chico	Concon	increasing	1.20	0.00
Norte chico	Los Andes	decreasing	-10.32	0.00
Norte chico	Puchuncavi	increasing	0.31	0.01
Norte chico	Campiche	decreasing	-1.16	0.00
Norte chico	La Greda	increasing	2.92	0.00
Norte chico	Los Maitenes	increasing	1.18	0.00
Norte chico	Ventanas	no trend	0.00	0.50
Norte chico	Cuerpo de Bomberos	decreasing	-0.43	0.00
Norte chico	La Palma	no trend	0.00	0.76
Norte chico	San Pedro	no trend	0.00	0.76
Norte chico	Centro Quintero	increasing	1.28	0.00
Norte chico	Loncura	no trend	-0.14	0.05
Norte chico	Quintero	increasing	1.36	0.00
Norte chico	Sur	decreasing	-0.92	0.00
Norte chico	Valle Alegre	no trend	-0.07	0.11
Norte chico	Vina del Mar	decreasing	-2.26	0.00
Zona centro	Cerrillos I	decreasing	-1.13	0.00
Zona centro	Cerro Navia	increasing	0.34	0.00
Zona centro	El Bosque	decreasing	-0.16	0.04
Zona centro	Independencia	decreasing	-0.32	0.01
Zona centro	La Florida	decreasing	-0.32	0.00
Zona centro	Las Condes	decreasing	-0.91	0.00
Zona centro	Pudahuel	decreasing	-0.27	0.00
Zona centro	Puente Alto	increasing	1.20	0.00
Zona centro	Quilicura I	decreasing	-2.60	0.00
Zona centro	Parque Ohiggins	decreasing	-0.45	0.00
Zona centro	Talagante	decreasing	-0.82	0.00
Zona centro	Codegua	decreasing	-1.12	0.00
Zona centro	Rengo	no trend	0.07	0.51
Zona centro	San Fernando	decreasing	-0.52	0.00
Zona centro	La Florida Talca	no trend	-0.07	0.26
Zona sur	Kingstone College	decreasing	-0.17	0.03
Zona sur	Coronel Sur	increasing	0.29	0.00
Zona sur	Lota rural	increasing	1.04	0.00
Zona sur	Lota urbana	increasing	2.17	0.00
Zona sur	ENAP Price	increasing	0.17	0.01
Zona sur	JUNJI	increasing	0.79	0.00
Zona sur	Hualqui	decreasing	-0.94	0.00
Zona sur	Indura	increasing	0.53	0.00
Zona sur	Liceo Polivalente	decreasing	-0.93	0.00
Zona austral	Coyhaique II	no trend	0.00	0.48

Table S8. National trend analysis for NOx concentrations (2000–2024) across Chile, organized by macrozone. The table displays the trend direction, the estimated slope (**ppbv yr^{-1}**), and the corresponding p-value for each monitoring station.

Macrozone	2000-2024	Trend	NOx ppbv yr^{-1}	P-value
Norte grande	Estación Centro	decreasing	-1.74	0.00
Norte grande	Jardin Infantil Integra	decreasing	-1.48	0.00
Norte grande	Escuela E-10	decreasing	-4.02	0.00
Norte chico	Colmo	increasing	0.59	0.00
Norte chico	Concon	increasing	0.44	0.00
Norte chico	Puchuncavi	no trend	0.21	0.43
Norte chico	Campiche	increasing	0.44	0.01
Norte chico	La Greda	decreasing	-0.68	0.00
Norte chico	Los Maitenes	no trend	-0.17	0.06
Norte chico	Ventanas	decreasing	-0.97	0.00
Norte chico	Cuerpo de Bomberos	decreasing	-0.92	0.00
Norte chico	La Palma	no trend	-0.10	0.60
Norte chico	San Pedro	no trend	-0.10	0.60
Norte chico	Centro Quintero	decreasing	-1.92	0.00
Norte chico	Quintero	no trend	0.07	0.84
Norte chico	Sur	decreasing	-0.72	0.00
Norte chico	Valle Alegre	increasing	0.69	0.00
Zona centro	Cerrillos I	increasing	5.39	0.00
Zona centro	Cerro Navia	decreasing	-4.82	0.00
Zona centro	El Bosque	decreasing	-6.61	0.00
Zona centro	Independencia	decreasing	-5.96	0.00
Zona centro	La Florida	decreasing	-3.77	0.00
Zona centro	Las Condes	decreasing	-0.49	0.05
Zona centro	Pudahuel	no trend	-0.06	0.92
Zona centro	Puente Alto	no trend	-1.42	0.07
Zona centro	Quilicura I	no trend	-1.95	0.57
Zona centro	Parque Ohiggins	decreasing	-4.77	0.00
Zona centro	Talagante	increasing	4.74	0.00
Zona centro	La Florida Talca	no trend	0.08	0.89
Zona sur	Punteras	no trend	0.30	0.12
Zona sur	Kingstone College	no trend	0.06	0.68
Zona sur	Coronel Sur	increasing	1.24	0.00
Zona sur	Lota rural	no trend	-0.04	0.86
Zona sur	Lota urbana	increasing	1.57	0.00
Zona sur	Hualqui	decreasing	-0.59	0.00
Zona sur	Consultorio San Vicente	decreasing	-2.39	0.01
Zona sur	Nueva Libertad	decreasing	-3.80	0.00
Zona sur	Liceo Polivalente	no trend	-0.20	0.13
Zona sur	Padre Las Casas II	increasing	0.96	0.04

Table S9. National trend analysis for NO concentrations (2000–2024) across Chile, organized by macrozone. The table displays the trend direction, the estimated slope (**ppbv yr^{-1}**), and the corresponding p-value for each monitoring station.

Macrozone	**2000-2024**	**Trend**	**NO ppbv yr^{-1}**	**P-value**
Norte grande	Estación Centro	decreasing	-1.91	0.00
Norte grande	Jardin Infantil Integra	decreasing	-0.61	0.00
Norte grande	Escuela E-10	increasing	2.26	0.00
Norte chico	La Calera	no trend	0.35	0.33
Norte chico	Rural 1	increasing	0.38	0.00
Norte chico	Colmo	increasing	0.15	0.03
Norte chico	Concon	decreasing	-0.23	0.04
Norte chico	Puchuncavi	no trend	0.17	0.40
Norte chico	Campiche	decreasing	-0.17	0.03
Norte chico	La Greda	decreasing	-0.27	0.04
Norte chico	Los Maitenes	increasing	0.37	0.00
Norte chico	Ventanas	decreasing	-0.50	0.00
Norte chico	Cuerpo de Bomberos	no trend	0.14	0.28
Norte chico	La Palma	increasing	0.62	0.00
Norte chico	San Pedro	increasing	0.62	0.00
Norte chico	Centro Quintero	decreasing	-1.08	0.00
Norte chico	Loncura	decreasing	-0.41	0.00
Norte chico	Quintero	decreasing	-1.23	0.00
Norte chico	Sur	decreasing	-0.42	0.00
Norte chico	Valle Alegre	increasing	0.28	0.00
Zona centro	Cerrillos I	increasing	3.35	0.00
Zona centro	Cerro Navia	decreasing	-5.12	0.00
Zona centro	El Bosque	decreasing	-5.72	0.00
Zona centro	Independencia	decreasing	-4.55	0.00
Zona centro	La Florida	decreasing	-4.69	0.00
Zona centro	Las Condes	decreasing	-1.06	0.00
Zona centro	Pudahuel	no trend	-0.40	0.47
Zona centro	Puente Alto	decreasing	-1.94	0.00
Zona centro	Quilicura I	no trend	-2.27	0.46
Zona centro	Parque Ohiggins	decreasing	-5.23	0.00
Zona centro	Talagante	increasing	2.81	0.00
Zona centro	Codegua	no trend	0.06	0.61
Zona centro	La Florida Talca	no trend	-0.29	0.33
Zona sur	Punteras	no trend	0.00	0.44
Zona sur	Kingstone College	decreasing	-0.29	0.00
Zona sur	Coronel Sur	increasing	0.91	0.00
Zona sur	Lota rural	no trend	0.04	0.67
Zona sur	Lota urbana	increasing	0.37	0.00
Zona sur	Hualqui	no trend	0.03	0.20
Zona sur	Consultorio San Vicente	decreasing	-1.33	0.00
Zona sur	Nueva Libertad	decreasing	-0.73	0.00
Zona sur	Liceo Polivalente	decreasing	-0.65	0.00
Zona sur	Padre Las Casas II	decreasing	-0.75	0.02
Zona austral	Coyhaique II	increasing	2.75	0.00

Table S10. National trend analysis for NO_2 concentrations (2000–2024) across Chile, organized by macrozone. The table displays the trend direction, the estimated slope (**ppbv yr^{-1}**), and the corresponding p-value for each monitoring station.

Macrozone	2000-2024	Trend	NO_2 ppbv yr^{-1}	P-value
Norte grande	Estación Centro	no trend	0.11	0.38
Norte grande	Jardin Infantil Integra	decreasing	-0.55	0.00
Norte grande	Escuela E-10	increasing	1.81	0.00
Norte grande	EME F	increasing	0.57	0.00
Norte grande	EME M	increasing	0.15	0.00
Norte chico	La Calera	decreasing	-0.34	0.03
Norte chico	Rural 1	decreasing	-0.82	0.00
Norte chico	Colmo	increasing	0.39	0.00
Norte chico	Concon	increasing	0.69	0.00
Norte chico	Puchuncavi	increasing	0.24	0.00
Norte chico	Campiche	decreasing	-0.29	0.00
Norte chico	La Greda	decreasing	-0.30	0.00
Norte chico	Los Maitenes	decreasing	-0.58	0.00
Norte chico	Ventanas	no trend	-0.19	0.07
Norte chico	Cuerpo de Bomberos	decreasing	-0.11	0.00
Norte chico	La Palma	decreasing	-0.06	0.04
Norte chico	San Pedro	decreasing	-0.06	0.04
Norte chico	Centro Quintero	decreasing	-0.96	0.00
Norte chico	Loncura	decreasing	-0.37	0.00
Norte chico	Quintero	increasing	1.45	0.00
Norte chico	Sur	no trend	-0.12	0.16
Norte chico	Valle Alegre	increasing	0.25	0.00
Zona centro	Cerrillos I	increasing	4.01	0.00
Zona centro	Cerro Navia	increasing	0.52	0.00
Zona centro	El Bosque	decreasing	-0.54	0.01
Zona centro	Independencia	decreasing	-1.50	0.00
Zona centro	La Florida	increasing	0.90	0.00
Zona centro	Las Condes	no trend	-0.01	0.82
Zona centro	Pudahuel	increasing	0.63	0.00
Zona centro	Puente Alto	increasing	0.42	0.02
Zona centro	Quilicura I	no trend	0.34	0.48
Zona centro	Parque Ohiggins	no trend	0.32	0.08
Zona centro	Talagante	increasing	1.41	0.00
Zona centro	Codegua	increasing	0.96	0.00
Zona centro	La Florida Talca	increasing	0.53	0.00
Zona sur	Punteras	increasing	0.23	0.01
Zona sur	Kingstone College	decreasing	-0.31	0.00
Zona sur	Lota rural	decreasing	-0.43	0.00
Zona sur	Lota urbana	increasing	1.32	0.00
Zona sur	ENAP Price	no trend	-0.06	0.54
Zona sur	JUNJI	no trend	-0.12	0.18
Zona sur	Hualqui	decreasing	-0.51	0.00

Macrozone	2000-2024	Trend	NO_2 ppbv yr^{-1}	P-value
Zona sur	Consultorio San Vicente	no trend	-0.30	0.24
Zona sur	Indura	decreasing	-0.59	0.00
Zona sur	Nueva Libertad	decreasing	-4.43	0.00
Zona sur	Liceo Polivalente	no trend	0.05	0.12
Zona sur	Padre Las Casas II	increasing	2.31	0.00

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