

Air Quality in São Paulo:

Lessons from Three Decades of Research



22 million
inhabitants



8 million
vehicles



Largest biofuel
fleet in the world



30 years
of emission
control



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MOTIVATION

What makes São Paulo unique



~20 million people

One of the world's largest megacities



~10 million vehicles

Predominantly flex-fuel fleet



Complex topography

Plateau, valleys and sea breeze



Mix of sources

Traffic, industry, biomass burning and regional transport



Remnant green areas

Potential for nature-based solutions

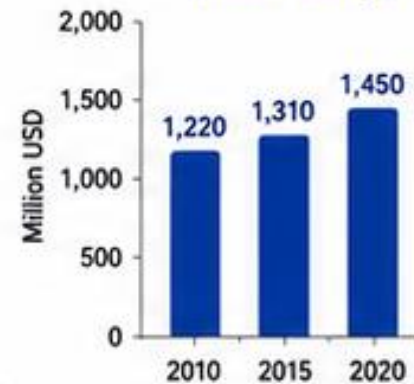


These characteristics require local data, advanced tools and integrated strategies tailored to our reality.

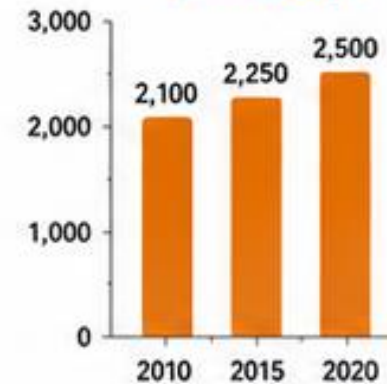


Economic costs in São Paulo (estimates)

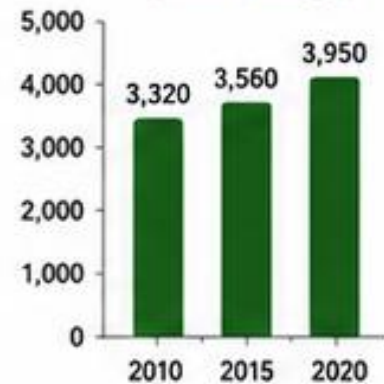
Health care costs
(million USD/yr)



Productivity losses
(million USD/yr)



Total cost
(million USD/yr)



Air pollution costs the São Paulo Metropolitan Area billions of dollars every year and reduces quality of life.

A Comprehensive Monitoring Network in São Paulo

Long-term measurements to understand air quality in a megacity

Monitoring infrastructure



26 air quality stations
CETESB automatic network



> 70 parameters
Gases, PM₁₀, PM_{2.5}, O₃, NO_x,
CO, SO₂, VOCs, meteorology



30+ years of data
Since the 1990s



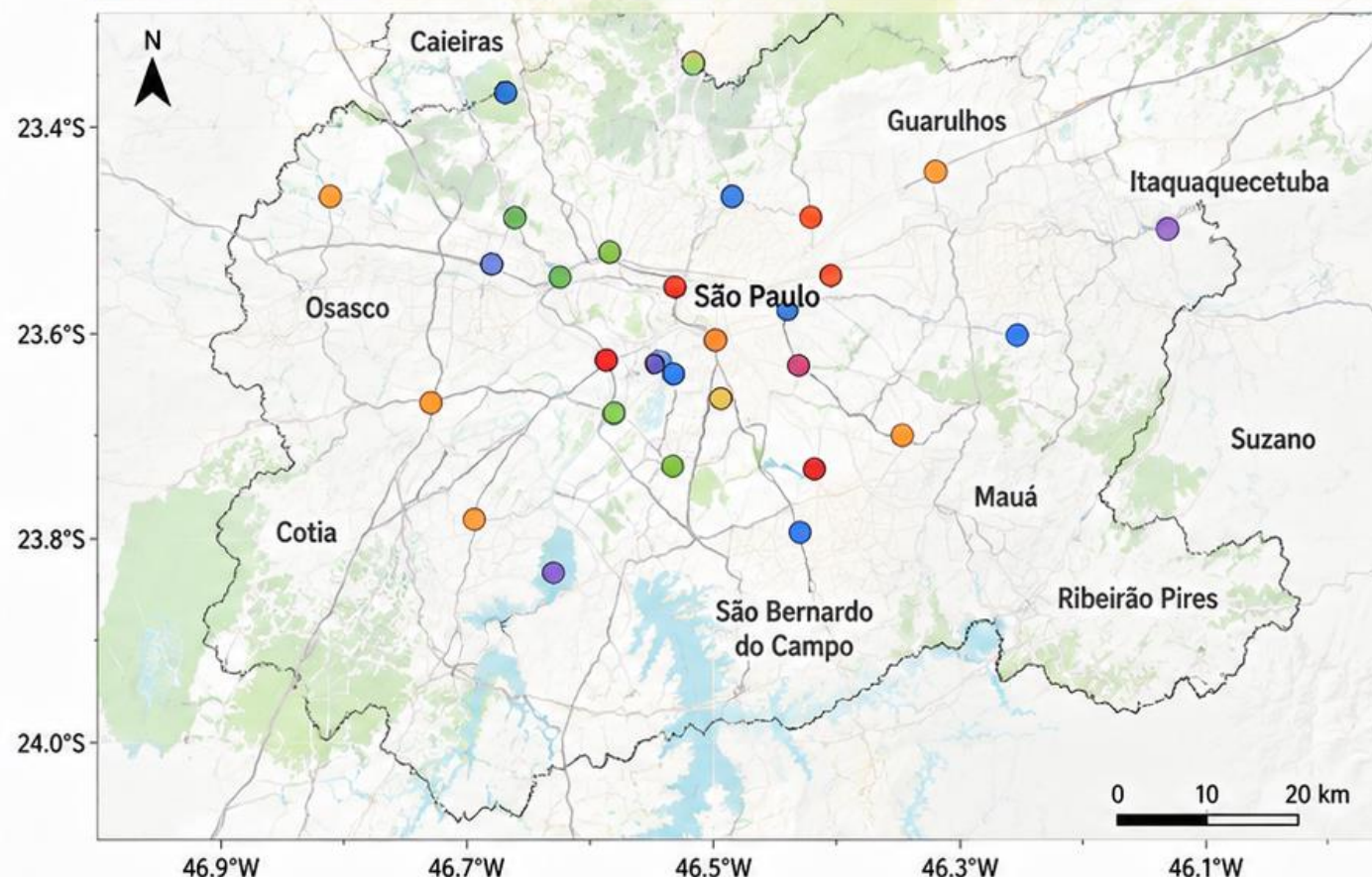
Support for science and society
Research, policies, and public
information

Additional measurement programs

- Greenhouse gases network (CO₂, CH₄)
- Aerosols and chemical composition
- Mobile laboratory and tunnel studies
- Flux tower and remote sensing



CETESB Air Quality Monitoring Stations



Station Type

- Traffic
- Industrial
- Urban Background
- Suburban
- Park / Rural

□ Metropolitan Area
of São Paulo (MASP)

63

stations in the
State of São Paulo

>1 million

hourly data per day



High-quality, long-term data are essential to assess trends,
identify sources, and evaluate policies.



Science²



Policies

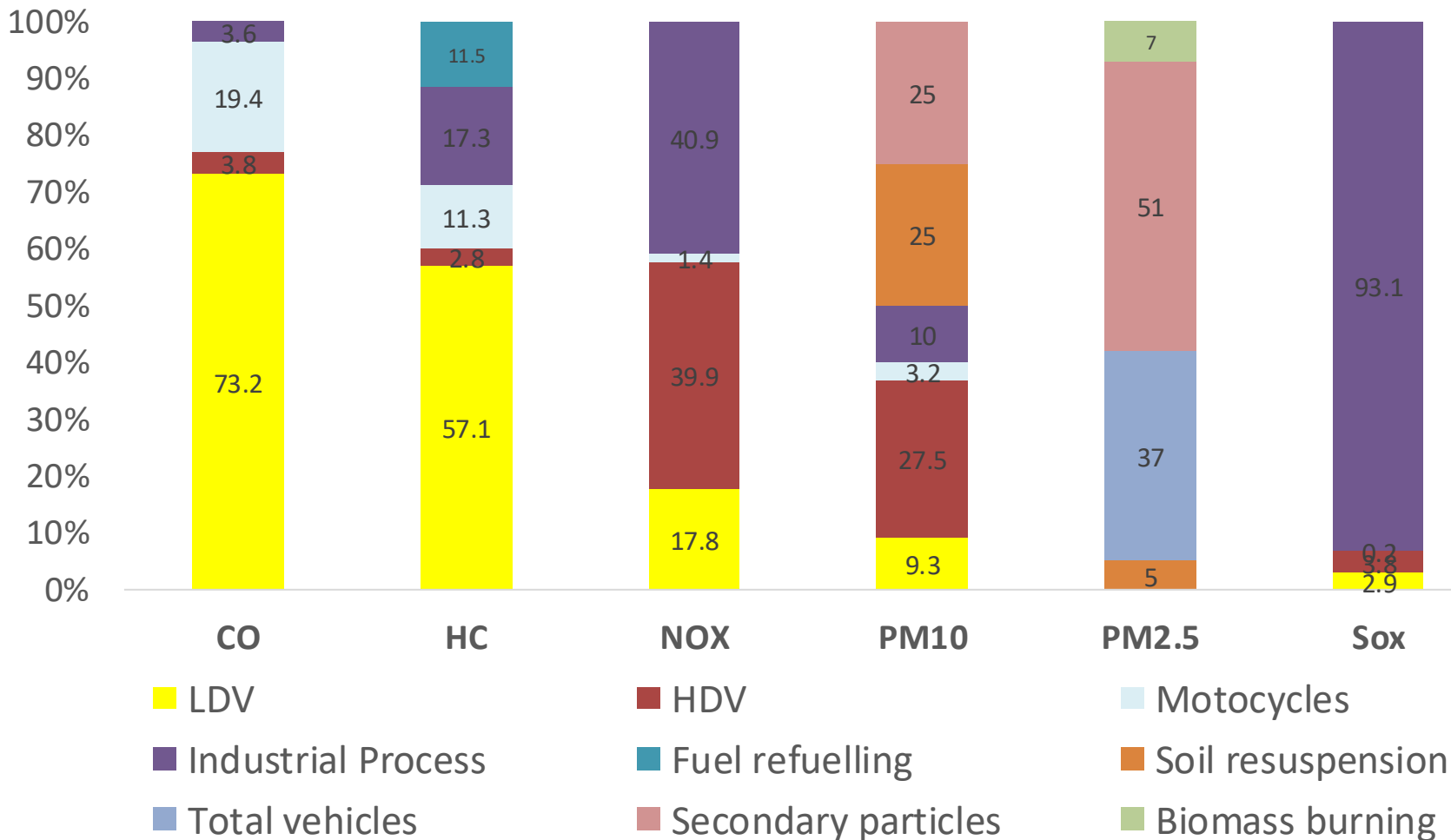


Health



Sustainable cities

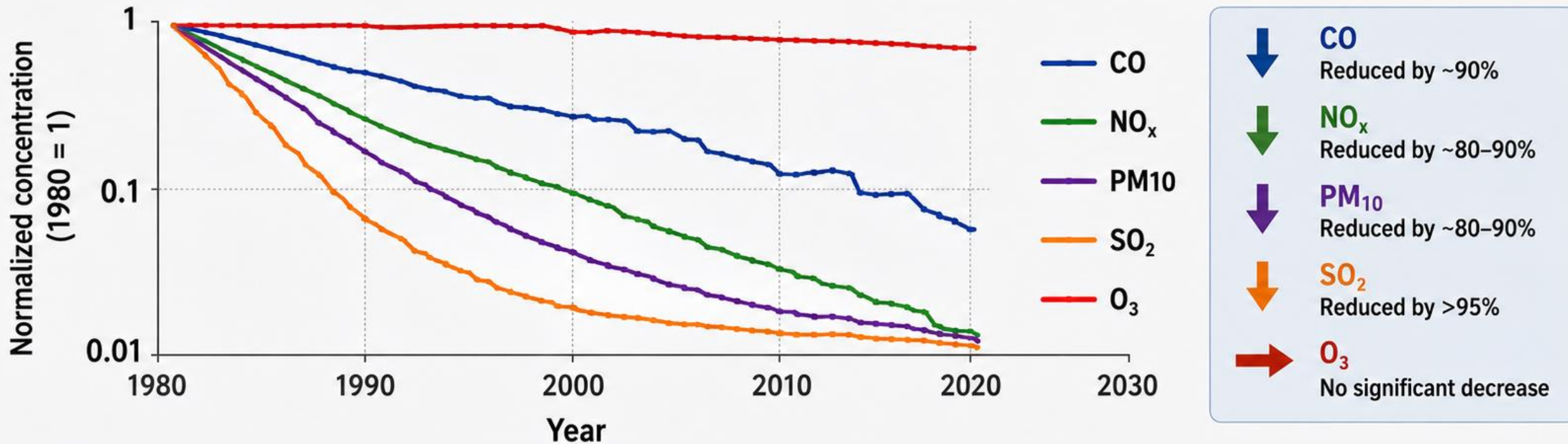
Pollutants emission by source type in the MASP



Source: CETESB, 2026

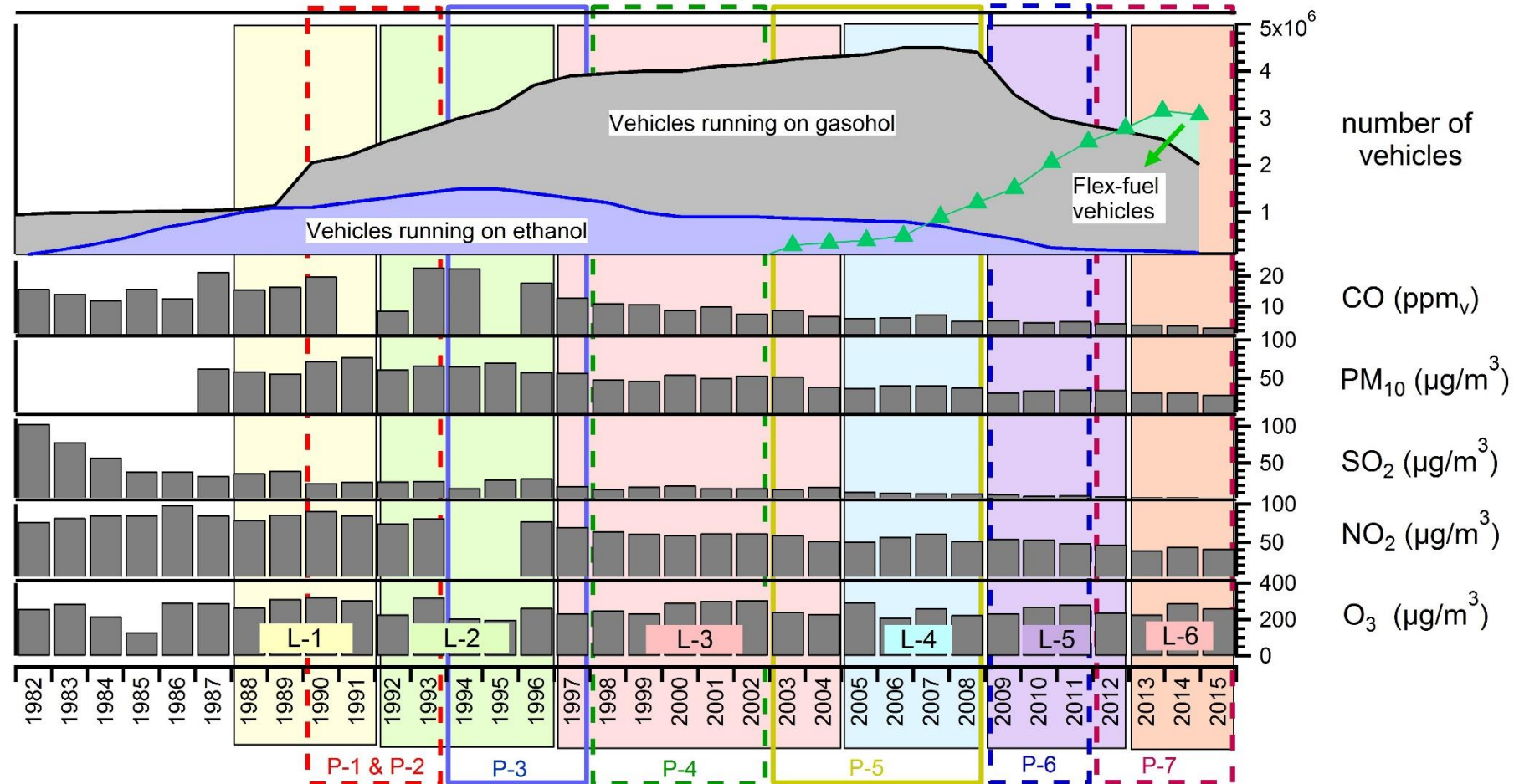
Emission control policies substantially improved primary air pollutants

São Paulo Metropolitan Area



Large reductions in primary pollutants, but ozone did not follow.

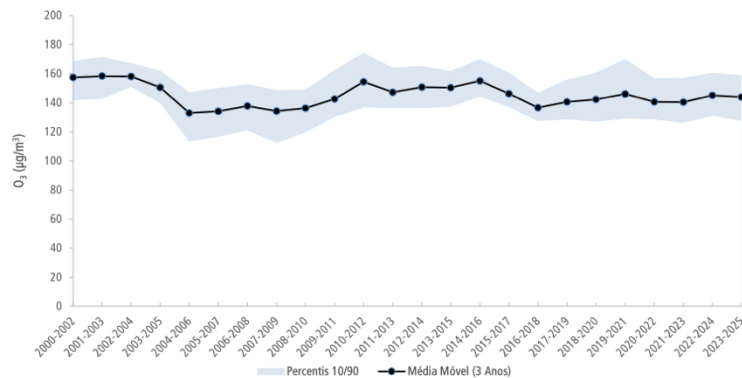
Evolution of the average values of CO, PM₁₀, O₃, SO₂ and NO₂ concentrations, and the year of implementation of the PROCONVE (Program for the Control of Air Pollution Emissions by Motor Vehicles phases).



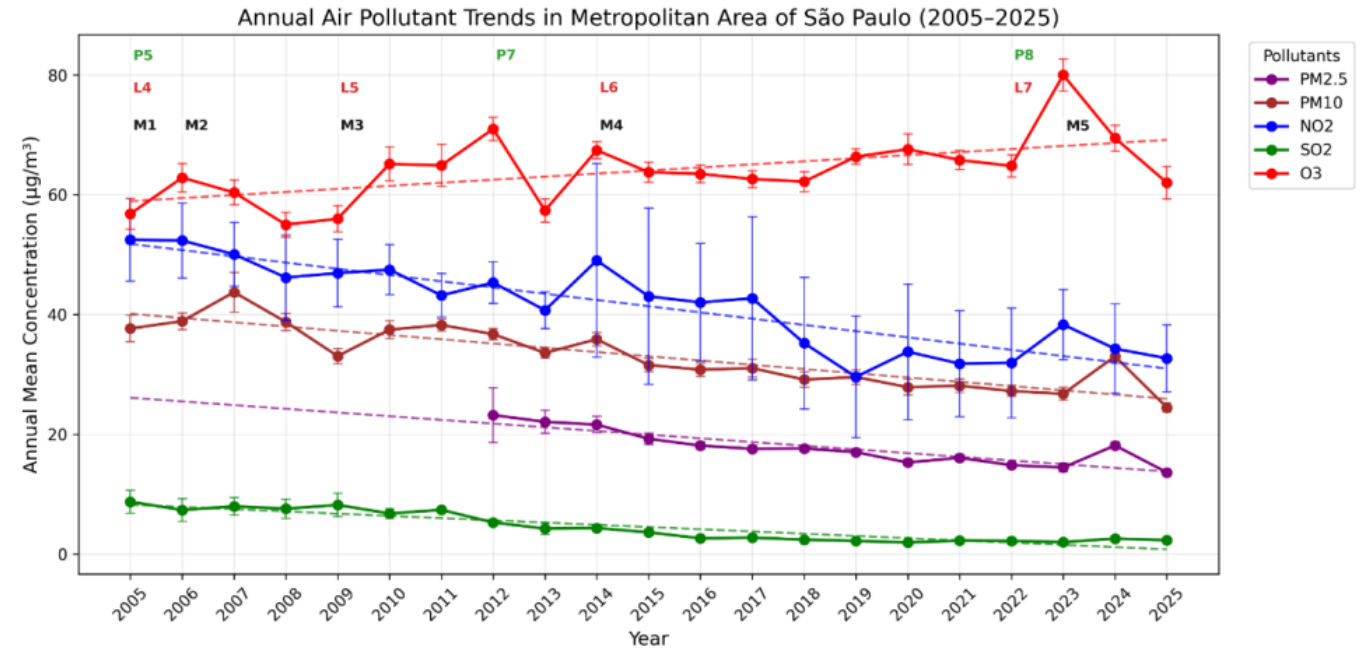
Long-term monitoring showed that emission control policies worked

14-YEAR EVIDENCE

- 2000-2025 monitoring network
- Most regulated pollutants declined
- O₃ was the clear exception



Mean annual concentrations for 4th maximum 8h mean O₃ in MASP



Annual concentration of CO, NO_x, O₃, and PM in the Metropolitan Area of São Paulo.

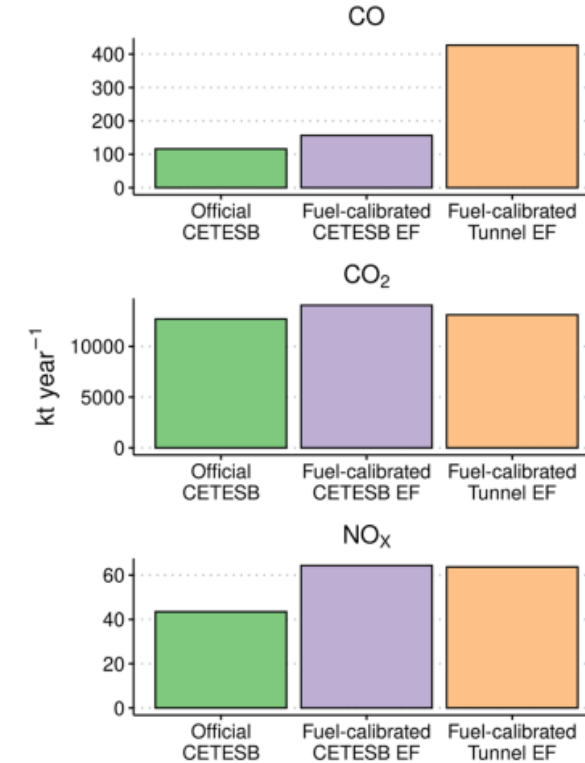
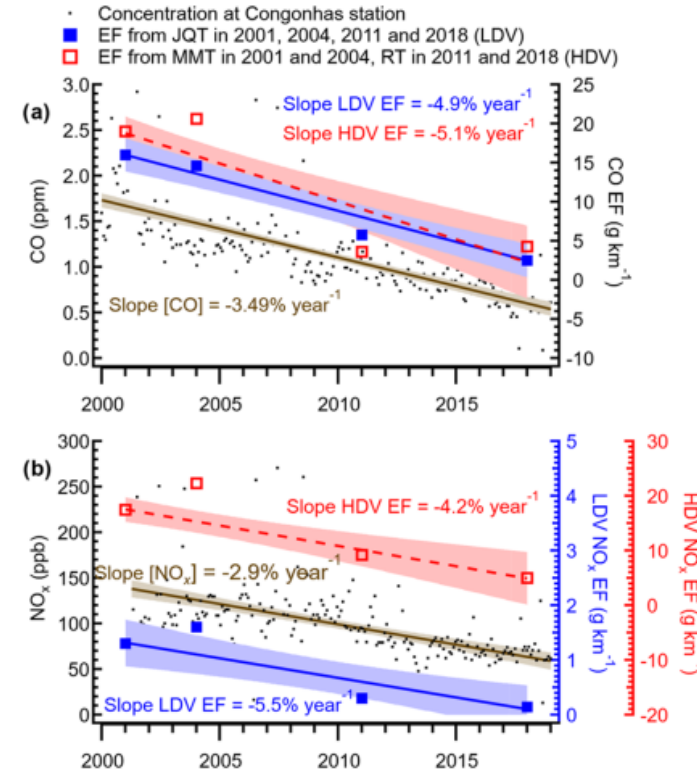
Primary pollution declined despite fleet growth — but ozone did not.

Two decades of tunnel campaigns confirmed strong emission-factor declines

2021

2001–2018

- CO EFs fell $\sim 5\%$ yr^{-1}
- NO_x EFs fell $\sim 4\text{--}6\%$ yr^{-1}
- Official inventories still underestimated some real-world emissions



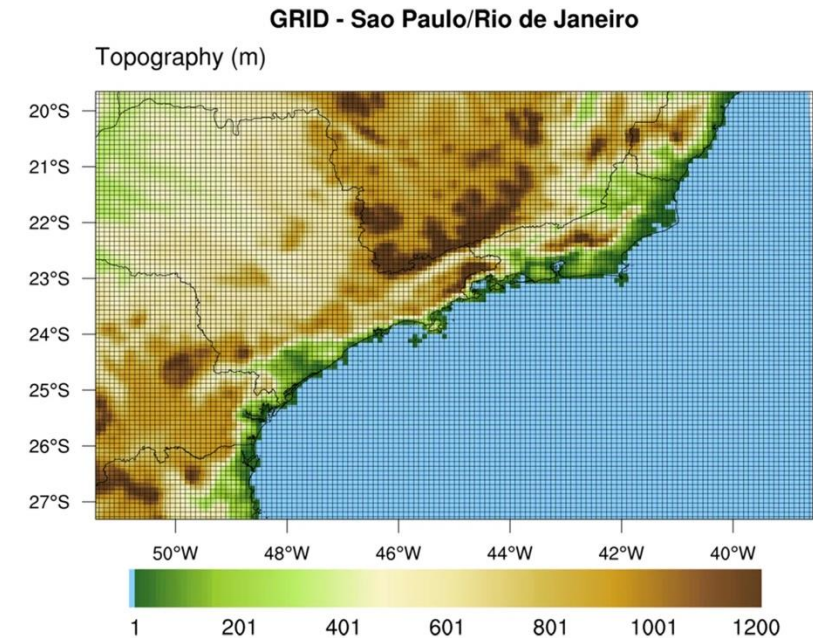
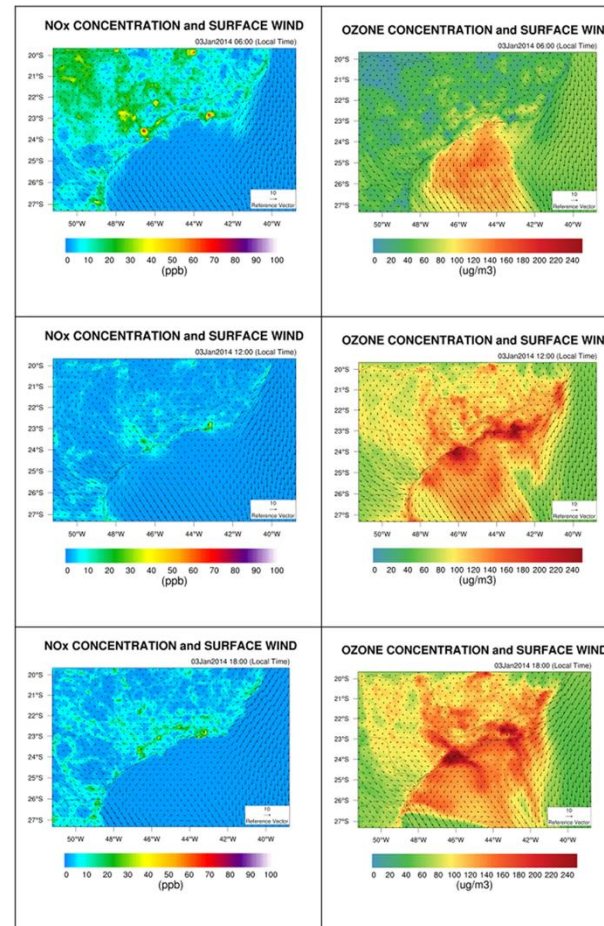
Regulation worked — with a measurable delay between standards and the in-use fleet.

Forecasting linked better emission factors to better air-quality prediction

2015

MODELING STEP

- WRF-Chem / BRAMS-SPM framework
- Street-level mobile-source allocation
- Biases pointed back to emission inventories



The modeling problem increasingly became an emissions-inventory problem.

Vehicular gases generated a substantial secondary PM_{2.5} burden

2016

WRF-CHEM EXPERIMENT

- 20–30% secondary PM_{2.5} downtown
- >40% of fine-particle formation linked to hydrocarbons
- Aromatics were especially important

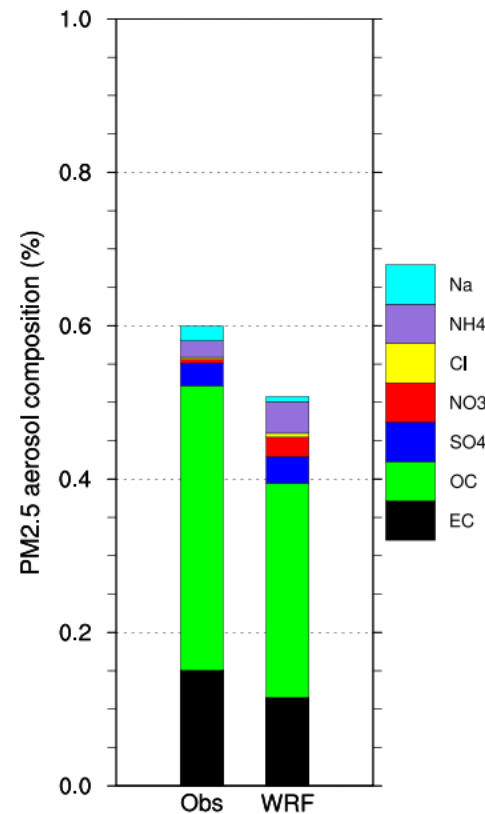


Figure 16. The observed and predicted average contributions for the main identified constituents of PM_{2.5} at LAG-USP.

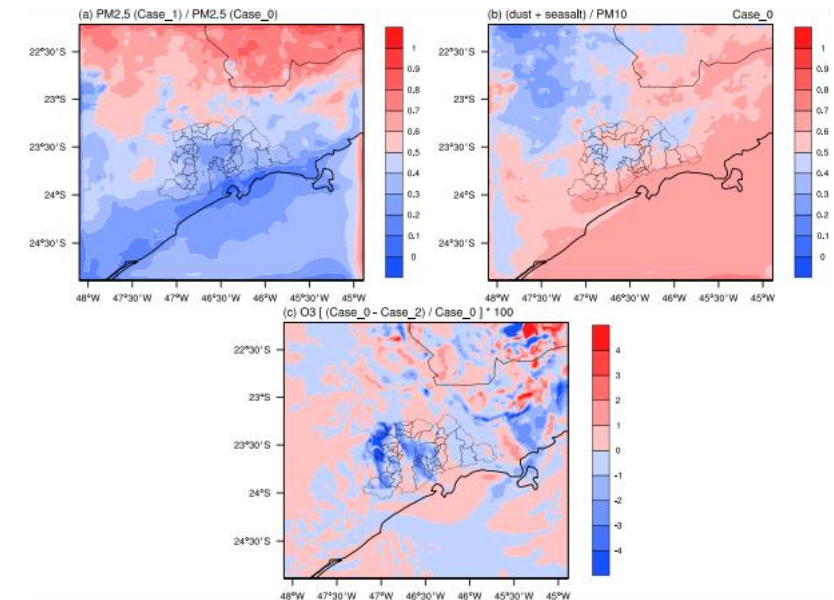


Figure 17. The impact of (a) emissions of primary gases on the fine particles formation, (b) emissions of dust-sea salt aerosols on the PM₁₀ concentration, and (c) aerosol direct effect on the ground level O₃ concentrations at 16:00 (local time).

Controlling particles requires controlling the gases that form particles.

VEIN moved vehicular inventories to street and hourly scales

2018

BOTTOM-UP INVENTORY

- Open-source R framework
- Exhaust + evaporative emissions
- Direct interface with WRF-Chem

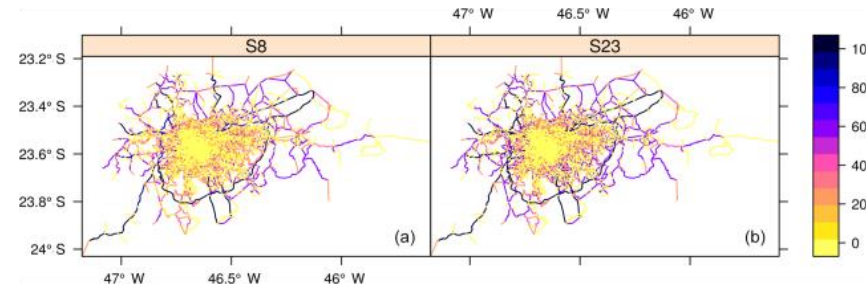


Figure 3. Traffic speeds (colored lines; km h^{-1}) for LDV fleet at 08:00LT (a) and 23:00LT (b) in MASP.

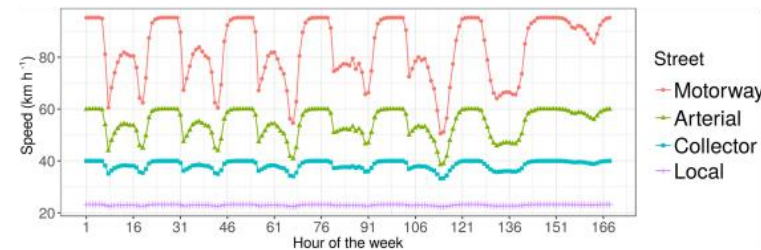


Figure 4. Traffic average speeds for LDV fleet by type of street (colored lines) at 08:00–09:00 LT in MASP.

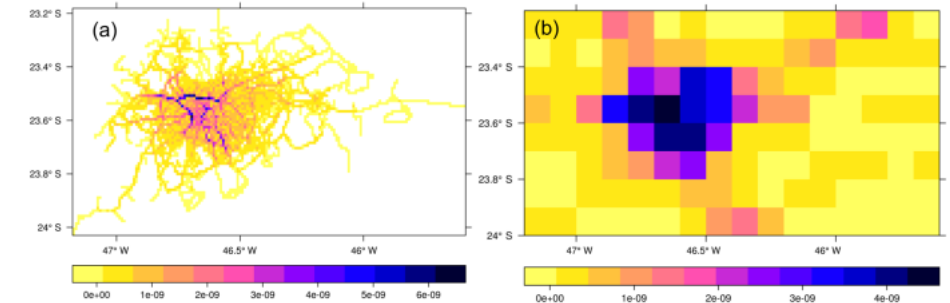


Figure 8. CO emissions ($\text{kg m}^{-2} \text{s}^{-1}$) in MASP for (a) Monday at 00:00:00 LT, estimated with VEIN; (b) the emissions of road transport for the same area from EDGAR.

High-resolution activity data made urban emission scenarios explicit and reproducible.

Using real-world emission factors improved modeled urban air quality

2021

CLOSING THE LOOP

- Tunnel EFs recalibrated the inventory
- WRF-Chem predictions moved closer to observations
- Measurement → inventory → model became one workflow

Environmental Science & Technology

pubs.acs.org/est

Article

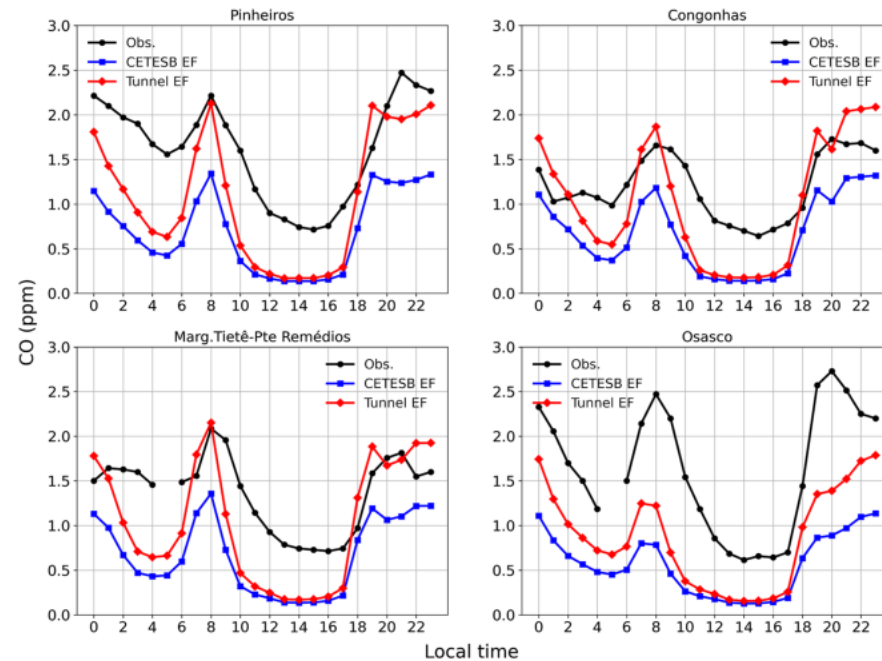


Figure 5. Diurnal cycle comparison between the observed values (Obs.), WRF-Chem simulation using fuel-calibrated CETESB EFs, and WRF-Chem simulation using fuel-calibrated tunnel EFs.

Better atmospheric models require better real-world emissions.

Real-world bus measurements quantified benefits of fleet modernization

2019

PUBLIC TRANSPORT

- Four bus-terminal experiments
- Euro II → Euro V + electric buses
- NO fell by a factor of 4–5; newer fleets emitted fewer particles

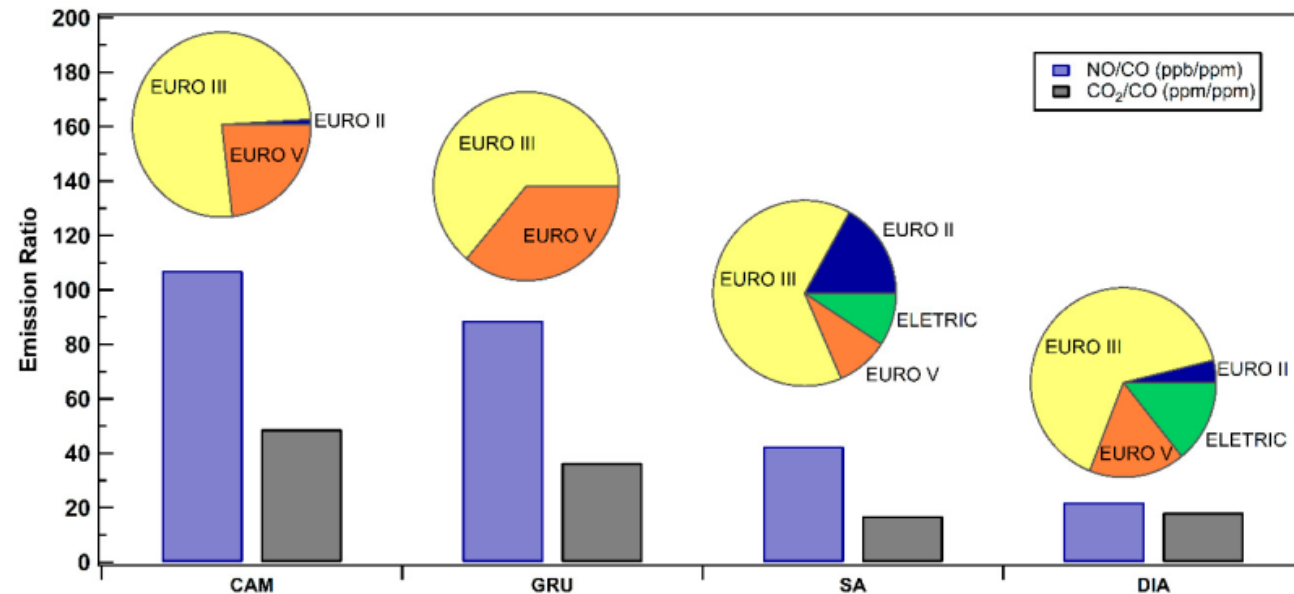


Figure 4. Emission ratios of CO₂ to CO (ppm/ppm, bars) and NO to CO (ppb/ppm, bars) observed at the four bus terminals (Campinas (CAM), Guarulhos (GRU), Santo André (SA), and Diadema (DIA)). The pie-charts represent the relative composition of the fleet in each bus terminal.

Fleet technology can deliver immediate exposure and air-quality benefits.

Particle number reveals exposure-relevant dynamics that PM mass can miss

2021

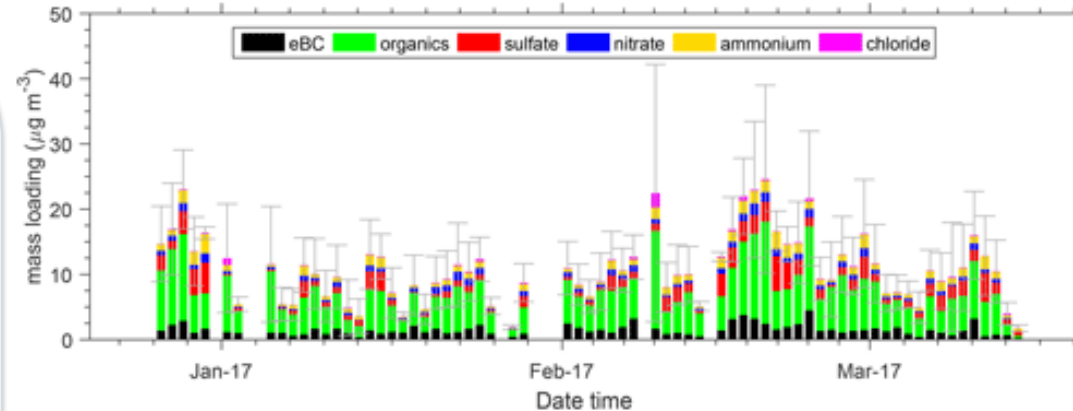
TOTAL PARTICLE NUMBER

$12,100 \pm 6,900$

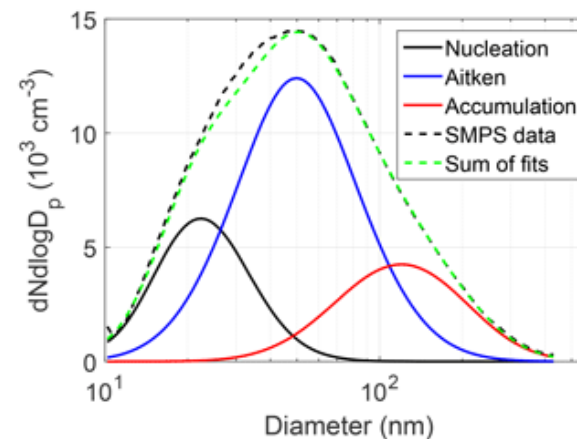
cm^{-3} (10–450 nm)

Measured every 2 min with SMPS during Dec 2016–Mar 2017 in Diadema, MASP.

PM₁ average mass: $11.4 \mu\text{g m}^{-3}$; organic aerosol dominated mass composition.



Time series of mass concentration of PM₁ chemical species.



Average particle number size distribution for measured and lognormal fits for nucleation, Aitken, and accumulation modes. Mean geometric diameter (and geometric SD) of the modes are 12.6 nm (1.2 nm), 30.7 nm (1.3 nm), and 83.8 nm (1.3 nm)

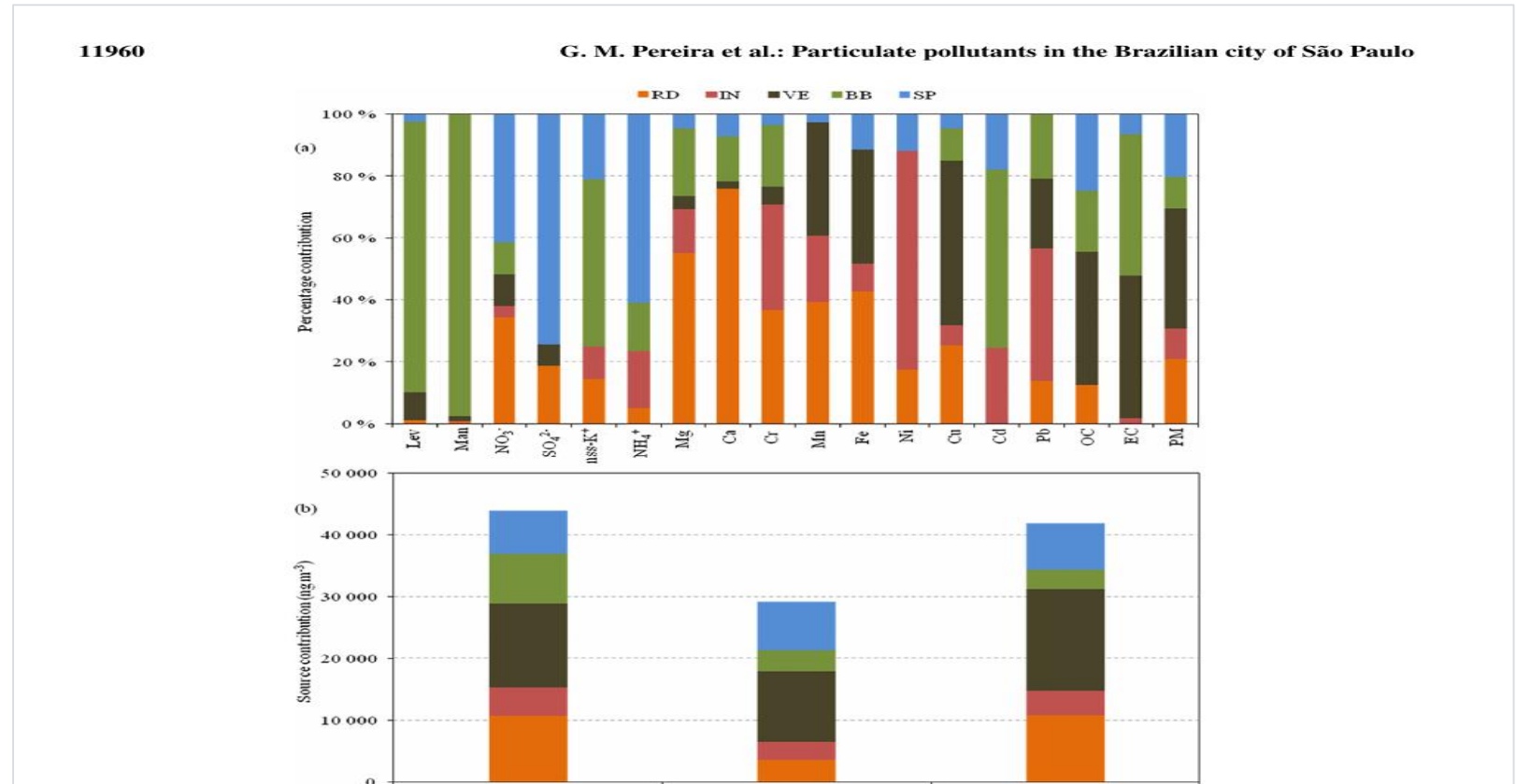
Number concentration adds a health- and process-relevant dimension beyond PM_{2.5} or PM₁ mass.

Year-round chemical speciation resolved five major PM source factors

2017

OBSERVED MIXTURE

- Road dust • industry • vehicles
- Biomass burning • secondary processes
- Winter enhanced biomass-burning and vehicular tracers



São Paulo PM is a mixture of local traffic, secondary chemistry and regional influence.

PMF-calibrated inventories improve PM_{2.5} simulations at urban sites

2026

A.H. Delgado Peralta et al.

Atmospheric Environment 383 (2026) 122249

LATEST STEP

- Global inventories calibrated with local PMF evidence
- Local road-transport emissions explicitly represented
- CMAQ evaluation targets PM_{2.5}, PM₁₀, CO and SO₂

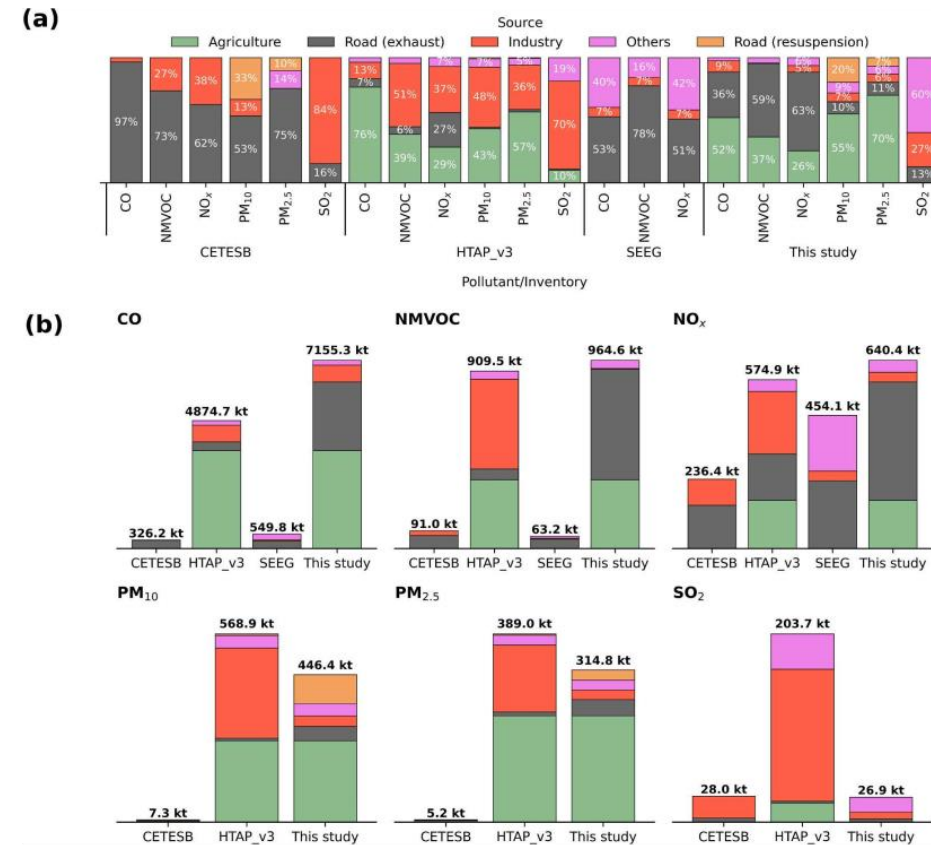


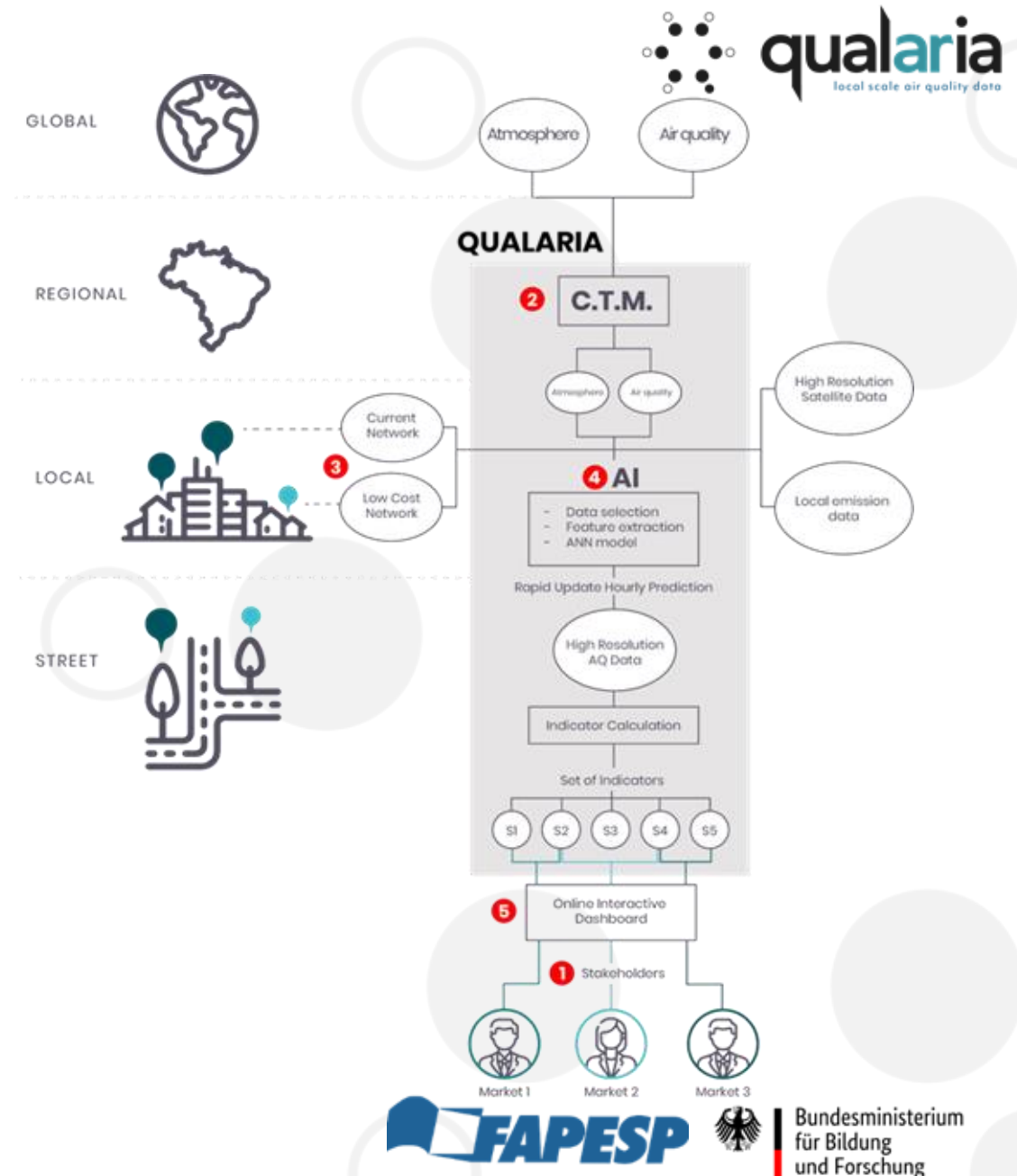
Fig. 2. Emissions of PM₁₀, PM_{2.5}, CO, NO_x, SO₂, and NMVOCs for the State of São Paulo in 2018, comparing four inventories (SEEG, EDGAR-HTAP_v3, CETESB, and this study) by source sector: (a) percentage contributions; and (b) annual emissions.

The research trajectory now converges on locally constrained, source-resolved modeling.

What is qualaria ?

local scale air quality data

- **QUALARIA** stands for: Artificial Intelligence based system for sub-urban scale air quality monitoring and prediction in the Metropolitan Area of São Paulo (MASP)
- A **joint Brazilian-German consortium** funded by FAPESP and BMBF
- **Main objective:**
To develop an AI-based air quality forecasting system with an online interactive dashboard to monitor and predict air quality in the Metropolitan Area of São Paulo (MASP) with high spatial resolution of 100 m.



Machine learning pipeline to simulate subgrid processes

Neural Network Architectures combine computer vision kernels to integrate regional-scale data and high-resolution terrain physical features to simulate subgrid climate variability

Input features (horizontal resolution):

- CAMS forecast data (40 km)
- WRF-Chem regional simulations (9/3 km)
- Topography and vegetation from satellite (30 m)
- Building heights (100 m)
- Vehicular emissions (100 m)

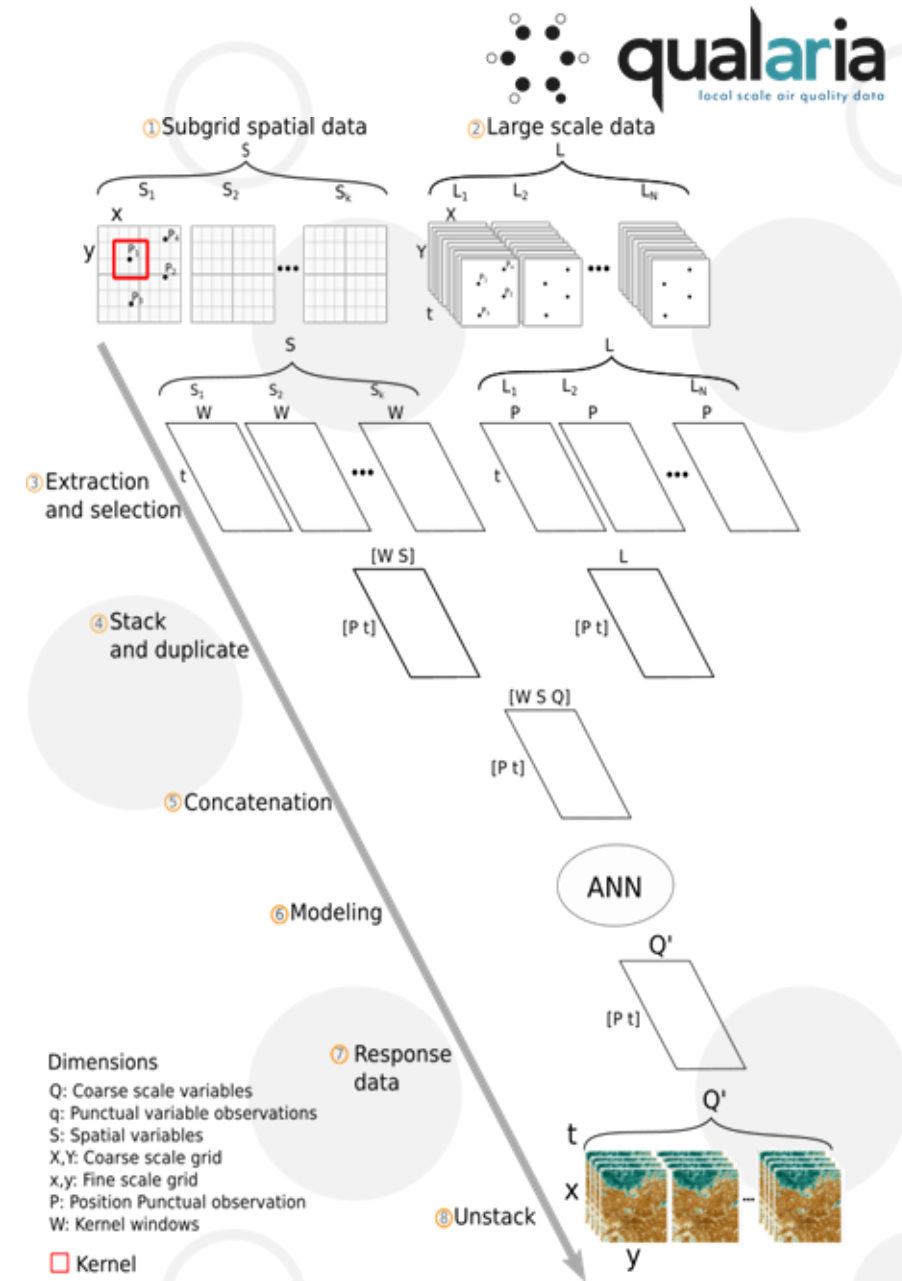
Target variables:

Observation data from CETESB stations and LCS sensors

Spatial/temporal resolution: 100 m/daily

Predictive horizons: 1 day ahead (to be extended to 5 days)

Operating frequency: daily



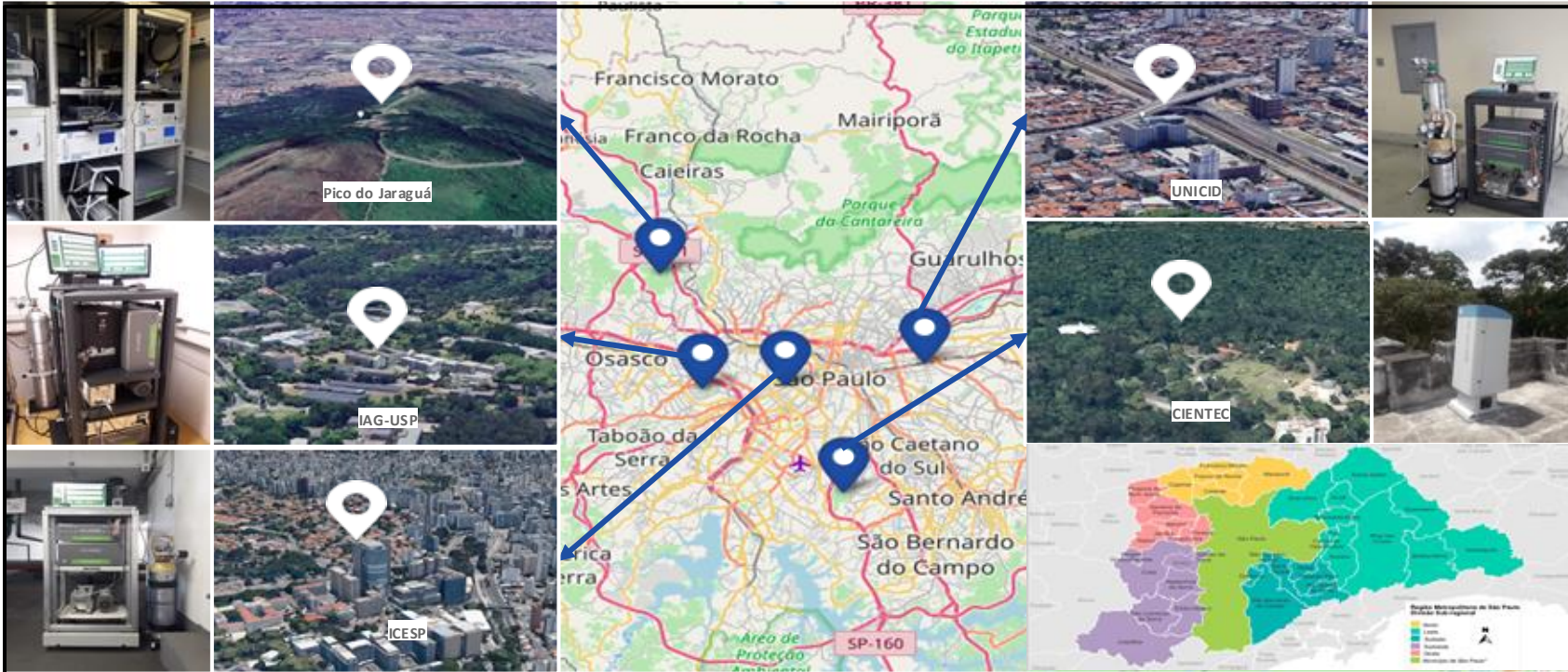
(Credit: MeteolA)

FAPESP Process 2016/18438-0

METROCLIMA

Jointly tracking climate change and air quality

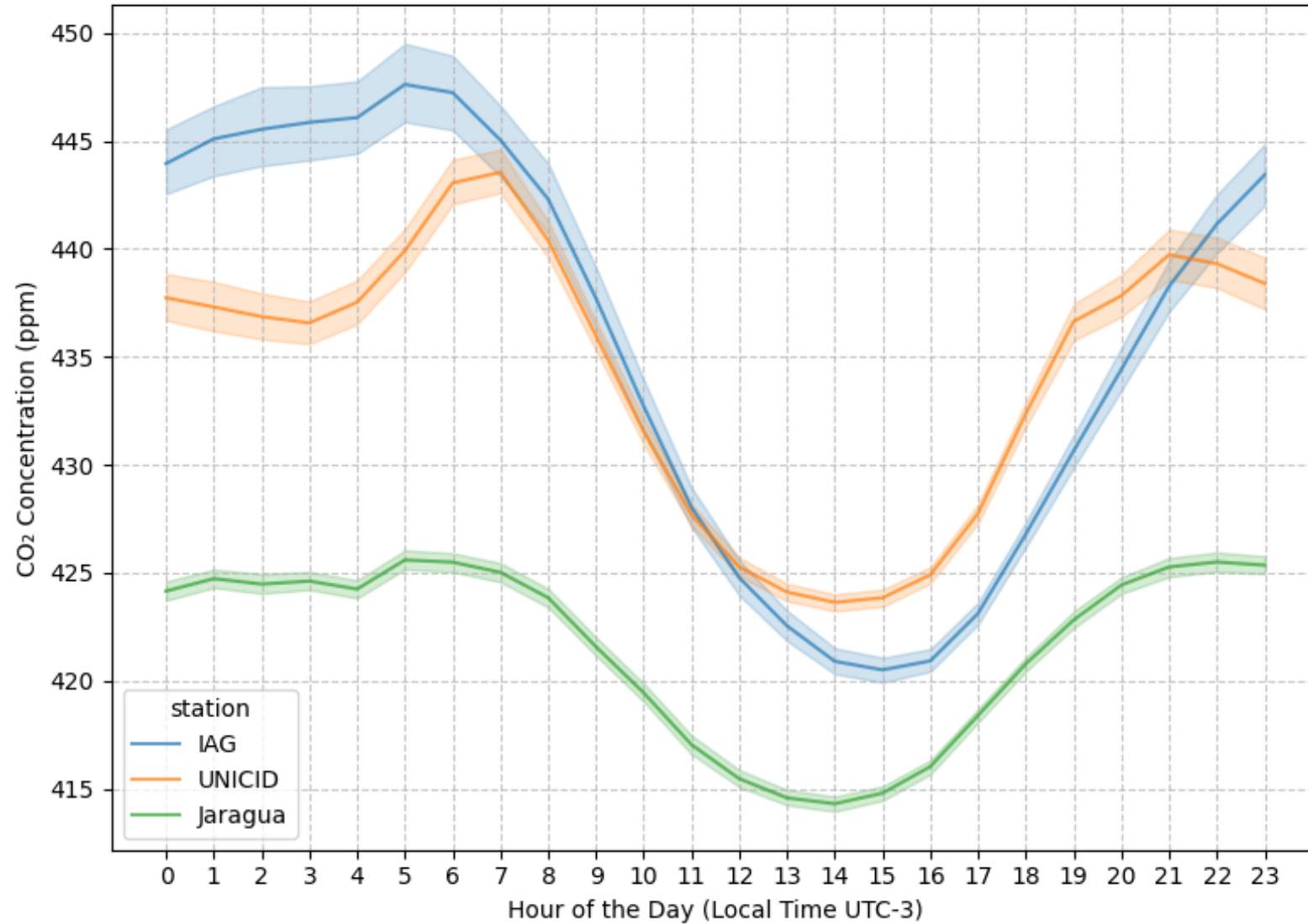
<http://www.metroclima.iag.usp.br/>



Project Framework

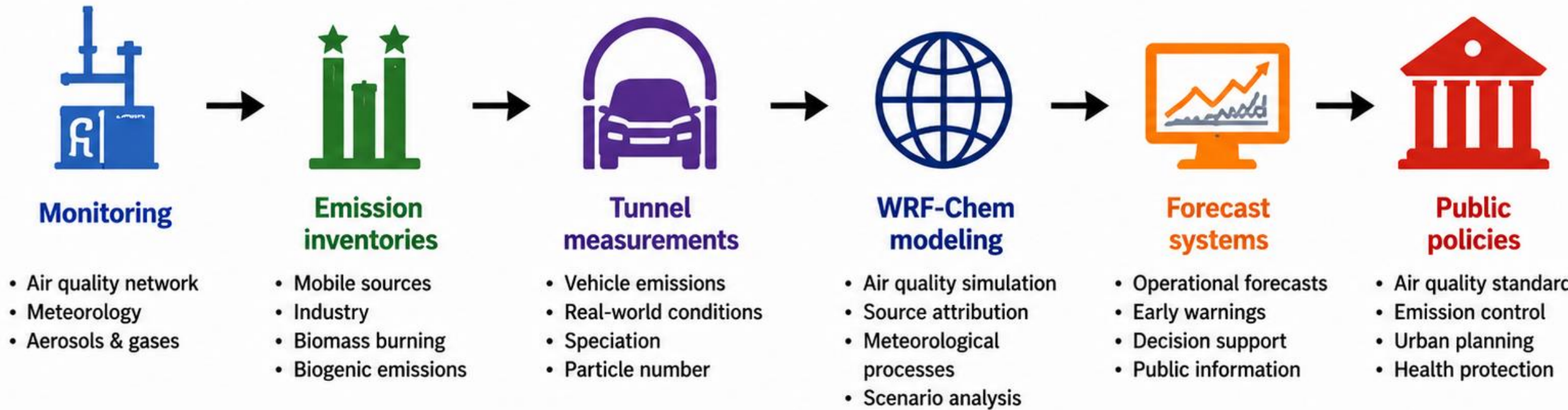


UNICID, IAG e Jaragua



Mean values
(2019-2024)

Understanding urban air quality requires an integrated approach



From observations to decisions:
science that supports effective air quality policies and protects public health.



São Paulo shows what long-term, integrated air-quality science can achieve

CONTROL WORKED

Primary emissions and ambient concentrations declined.

CHEMISTRY REMAINS

O₃ and secondary PM respond nonlinearly to precursor changes.

LOCAL EVIDENCE MATTERS

Real-world EFs, PMF and regional evaluation improve models.

Next step: integrate emissions, atmospheric chemistry, exposure and urban carbon in one decision framework.

Thank you! Obrigada!



São Paulo Research
Foundation



National Council for
Scientific and Technological
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Coordination for the
Improvement of Higher
Education Personnel



Global Environment
Facility



World Meteorological
Organization
(GAW / GURME)



Institute of Science and
Technology for Climate
Change



FAPESP Thematic Project –
São Paulo Metropolitan Area



NERC–FAPESP Project
UK / Brazil



PM-Kidney
FAPESP Project



Global Consortium on
Atmospheric Research
and Environment

