Integrating Satellite and Sensor Measurements to Understand Urban Air Quality: A Case Study of $PM_{2.5}$ in Asunción, Paraguay

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This article describes a collaborative approach to obtaining fine particulate matter concentration estimates when no or limited data exists, using a case study for Asunción, Paraguay.

Air pollution can be a major public health concern in many cities throughout the world, especially in locations with high levels of ambient fine particulate matter ($PM_{2.5}$). Exposure to $PM_{2.5}$ can increase risks for numerous adverse health effects including lung cancer, lower-respiratory infections, ischemic heart disease, adverse birth outcomes, and premature mortality.[1,2] Because of the health consequences from exposures to $PM_{2.5}$, the World Health Organization (WHO) recommends that annual average $PM_{2.5}$ levels not exceed 5 $\mu g/m^3$ and 24-hr averages not exceed 15 $\mu g/m^3$.[3,4] However, quantifying $PM_{2.5}$ exposures and public health concerns can be challenging when a region lacks air quality monitoring, a common situation throughout the world. This article describes a collaborative approach to obtaining $PM_{2.5}$ concentration estimates when no or limited data exists, using a case study for Asunción, Paraguay.

Methodology

In the absence of regular, long-term $PM_{2.5}$ monitoring data, alternatives were explored to estimate $PM_{2.5}$ concentrations in Asunción, Paraguay. Asunción's elevation ranges between 50 m and 196 m above sea level, and it experiences a subtropical climate with heaviest rainfalls occurring from October to April.[5,6] Approximately 3.39 million residents live in the Asunción urban area.[7-9] Major sources of air pollution in Paraguay include agricultural, biomass, and fossil fuel burning for transportation and power generation.[10] To provide estimates of $PM_{2.5}$ concentrations, two techniques were employed: satellite and ground-level sensor measurements.

Satellite Data. For regions with no historical air pollution monitoring, satellite measurements can be an important resource to estimate concentrations and exposures for the local population.[11] Satellites measure the scattering of light due to particles and gases present in an atmospheric column from the ground to space, usually once per day although the time resolution depends on the satellite platform. Various techniques can be used to convert satellite measurements to ground-level concentrations, such as the use of chemical transport modeling, followed by regression analyses with ground-level monitoring data to constrain the pollutant concentration estimates.

For Asunción, data from van Donkelaar[12] provided annual and monthly $PM_{2.5}$ concentration estimates. This dataset combines Aerosol Optical Depth measurements from

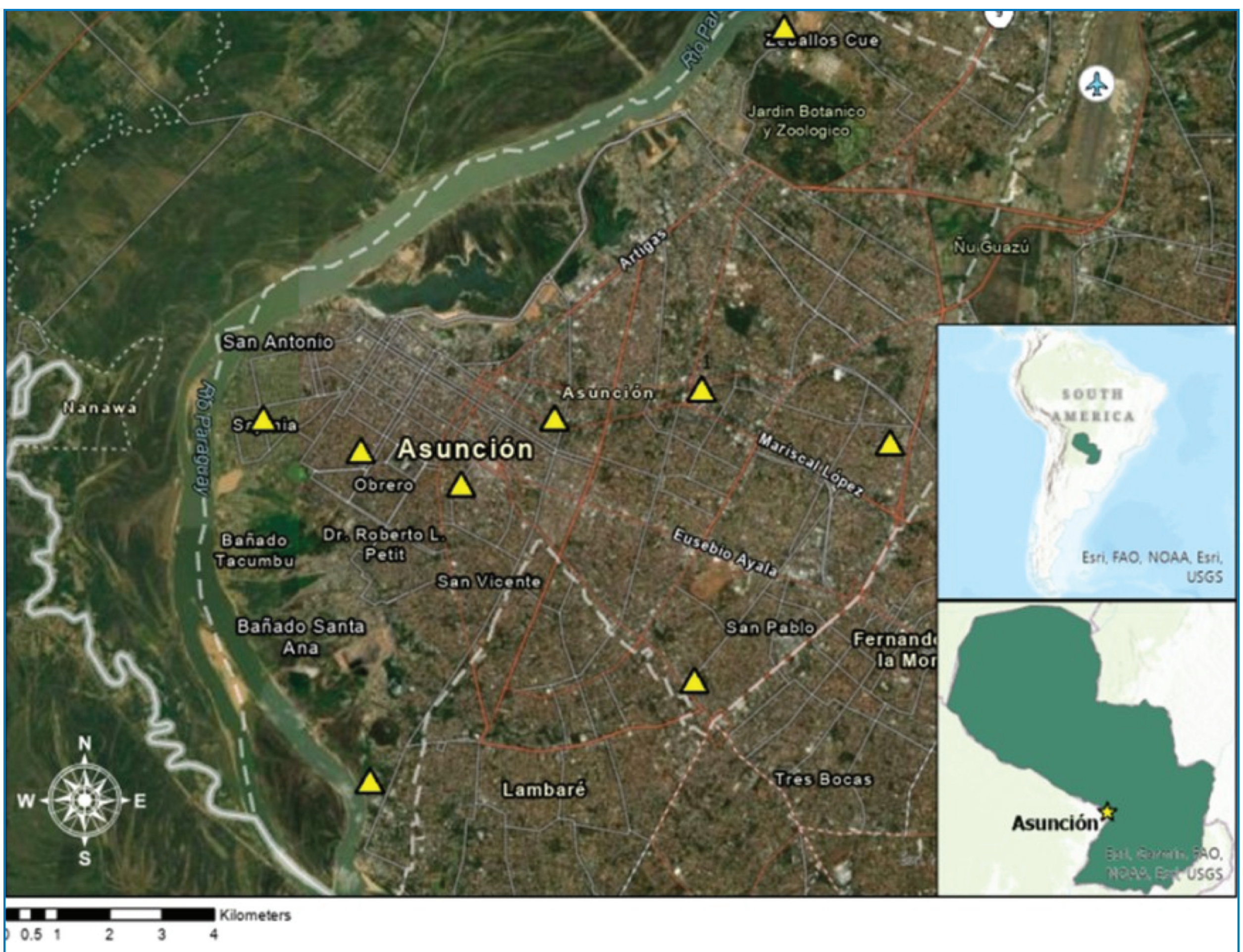

Figure 1. Map of Asunción, Paraguay.
Note: Yellow triangles show the locations of Aire Paraguay's ground-level sensors.

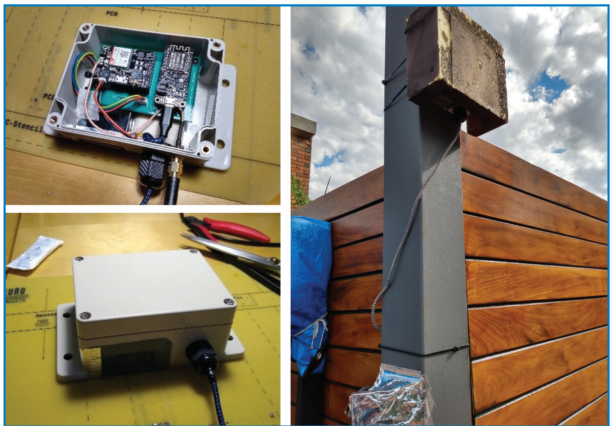

Figure 2. Sensor exterior and interior configurations with an example installation setup in Asunción containing a heat shield.

multiple satellites with the GEOS-Chem chemical transport model. The data are calibrated to ground-level monitor measurements, where available, using geographically weighted regression techniques. These global estimates are gridded at a resolution of 0.01° × 0.01°, roughly 1 × 1 km.[12]

Ground-Level Sensor Data. The ground-level monitoring network uses Sensirion SPS30 laser-scattering $PM_{2.5}$ sensors (Sensirion AG, Switzerland). The network was initiated in 2019 in Asunción and other cities in Paraguay to provide the first, longer-term air quality monitoring data set in Paraguay.[13]

The $PM_{2.5}$ sensors are enclosed in weatherproof boxes for unattended, remote operation. Some sensors also have heat shields to maintain temperatures below 60 °C when exposed to direct sunlight. Wireless communication allows for remote data downloading and equipment checks. $PM_{2.5}$ concentrations reported by the sensors are based solely on factory-calibration and manufacturer algorithms. These data are recorded at 5-min averages, with daily and annual average concentrations determined by post-processing.

Figure 1 shows the sensor locations in Asunción, while Figure 2 shows the sensors and an example site. Measurements from January 2020 to May 2021 were evaluated since all sensors were operational in the monitoring network during this time. For data analysis, missing or zero reported values were removed and not included in calculations. In addition, only data falling between the 75th and 25th percentile of measured data were considered in this initial data analysis. This conservative approach was used to reduce the impact of local events very close to a sensor, such as smoking or food grilling, which would not represent ambient air quality concentrations.

Results

Satellite data provided insights on regional $PM_{2.5}$ concentrations in Asunción. Figure 3 shows an example of an average monthly $PM_{2.5}$ measurement for February 2020. As shown, this monthly average exceeded 10 μg/m³ for much of Asunción. While the measurements across South America indicated regions of even higher pollution concentrations, $PM_{2.5}$

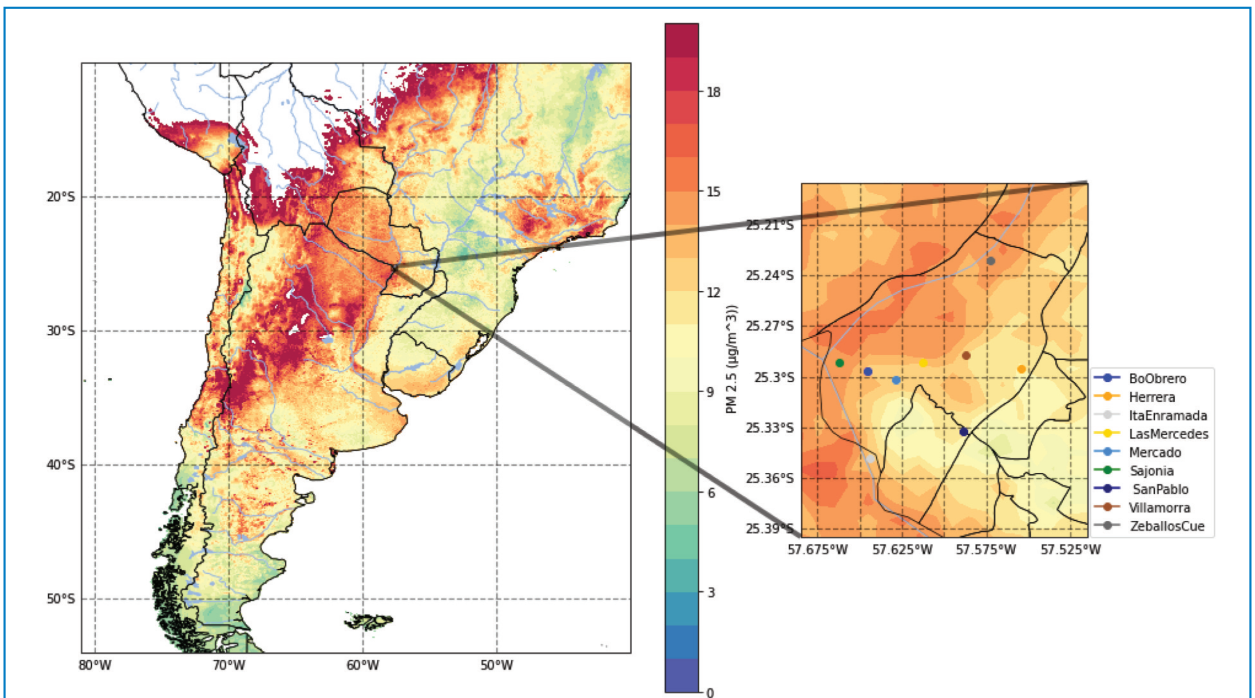

Figure 3. Satellite-derived monthly averaged $PM_{2.5}$ concentrations for South America and Asunción during February 2020.[12]

Note: Locations of ground-level sensors also shown for Asunción in the panel to the right.

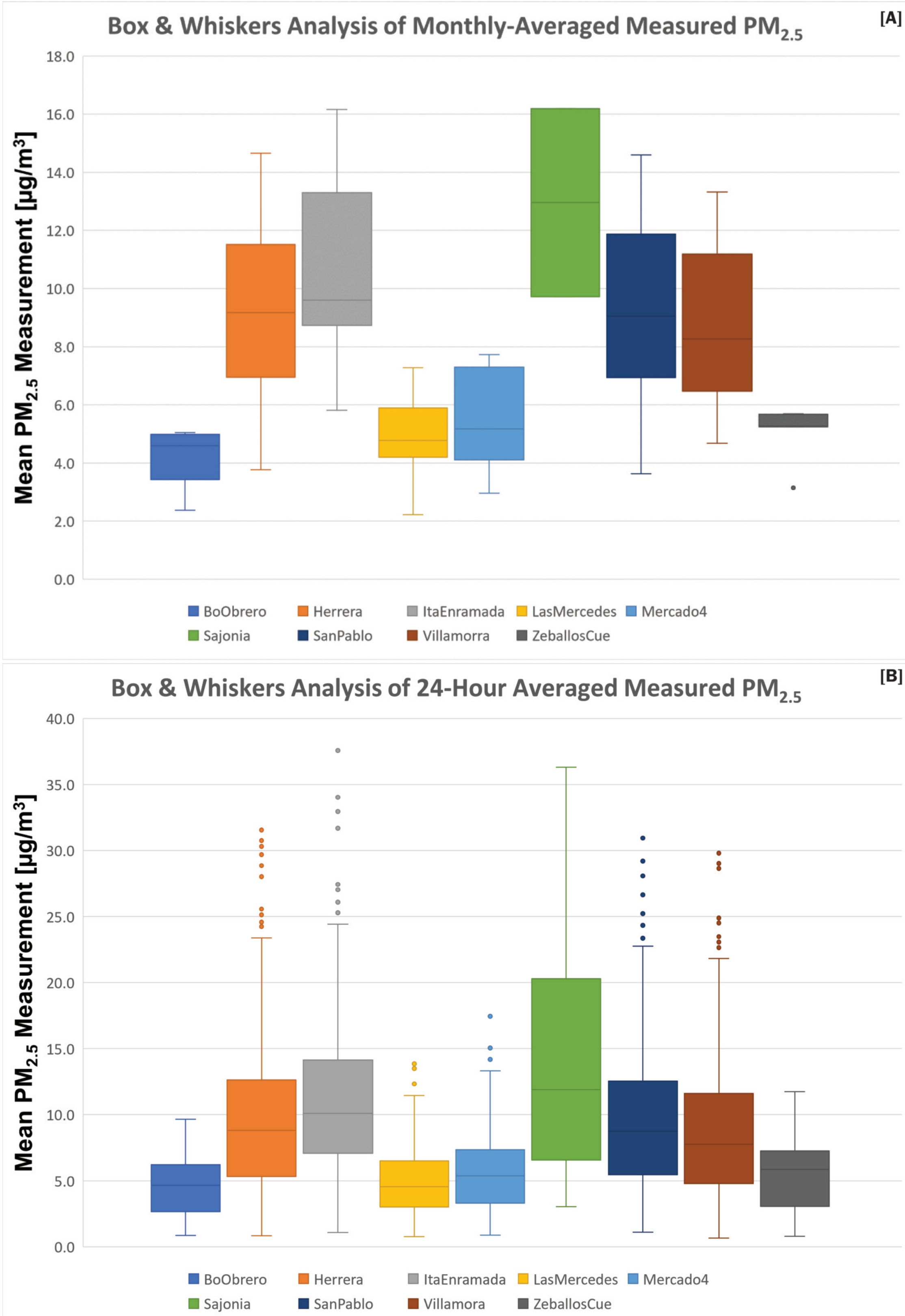

Figure 4. Box-and-whisker plots showing the distributions of monthly mean $PM_{2.5}$ values (4A) and 24-hr $PM_{2.5}$ mean values (4B) for each ground-level sensor.[13]

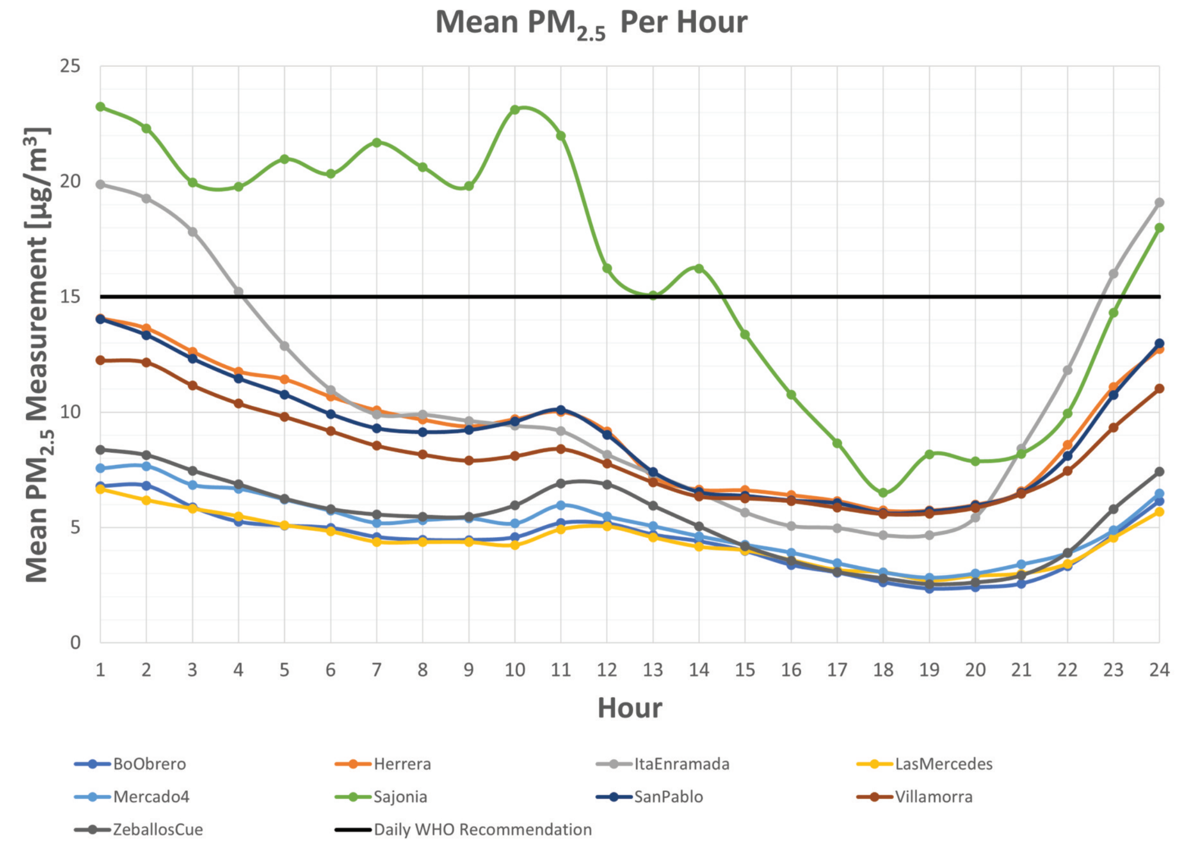

Figure 5. Line graph showing hourly $PM_{2.5}$ averages for each ground-level sensor.[13]
Note: The black line shows the WHO's daily $PM_{2.5}$ recommended standard for reference.

in Asunción was relatively high. The satellite measurements suggest that some residents of Asunción, particularly in the north and west, experienced a monthly average $PM_{2.5}$ concentration above the WHO daily recommended maximum of 15 µg/m³, indicating a potential sustained exposure above recommended health levels. Figure 3 also shows the locations of the ground-level sensor measurements in Asunción, which satellite data suggested averaged from 10 to 14 µg/m³ during this month, lower than other parts of the city.

While the satellite data provided useful information on regional-scale spatial distributions of $PM_{2.5}$ concentrations, these data are limited in identifying temporal and local-scale variations in $PM_{2.5}$ impacts caused by nearby sources of air pollution, as shown in Figure 4. An evaluation of the ground-level sensor measurements highlighted potentially extensive temporal and spatial variability of $PM_{2.5}$ in Asunción. Figure 4A shows the distribution of monthly average $PM_{2.5}$ values for each sensor monitoring location. Note that some sensors did not operate consistently during the entire period analyzed (January 2020–May 2021), so not all distributions are directly comparable. The measurement distributions suggested that some locations (BoObrero, Las Mercedes, and Mercado) may experience lower average $PM_{2.5}$ values than other locations (Herrera, ItaEnramada, and Sajonia).

While the satellite data in Figure 3 did not suggest a significant difference in monthly averaged $PM_{2.5}$ levels among the sensor locations, the results in Figure 4A suggest much greater variability, with mean differences potentially a factor of 3 between sites, provided each sensor's manufacturer reported accuracy and precision specifications were maintained. This result could indicate that local sources influenced $PM_{2.5}$ concentrations at some locations in Asunción. Also, for the satellite data, local $PM_{2.5}$ gradients may not be fully resolved due to influences from coarser resolution information sources in compiling the data.[12]

Since the ground-level sensors can provide even higher temporal resolution data, Figure 4B shows a comparison of average 24-hr daily $PM_{2.5}$ distributions. Comparing Figure 4A and Figure 4B suggest similar spatial trends at each site for the monthly and daily average $PM_{2.5}$ concentrations, respectively. Figure 4B also indicates that the WHO daily standard of 15 µg/m³ was potentially exceeded at many of the sites.

Figure 5 presents a comparison of hourly $PM_{2.5}$ trends for each monitoring site. These measurements indicate

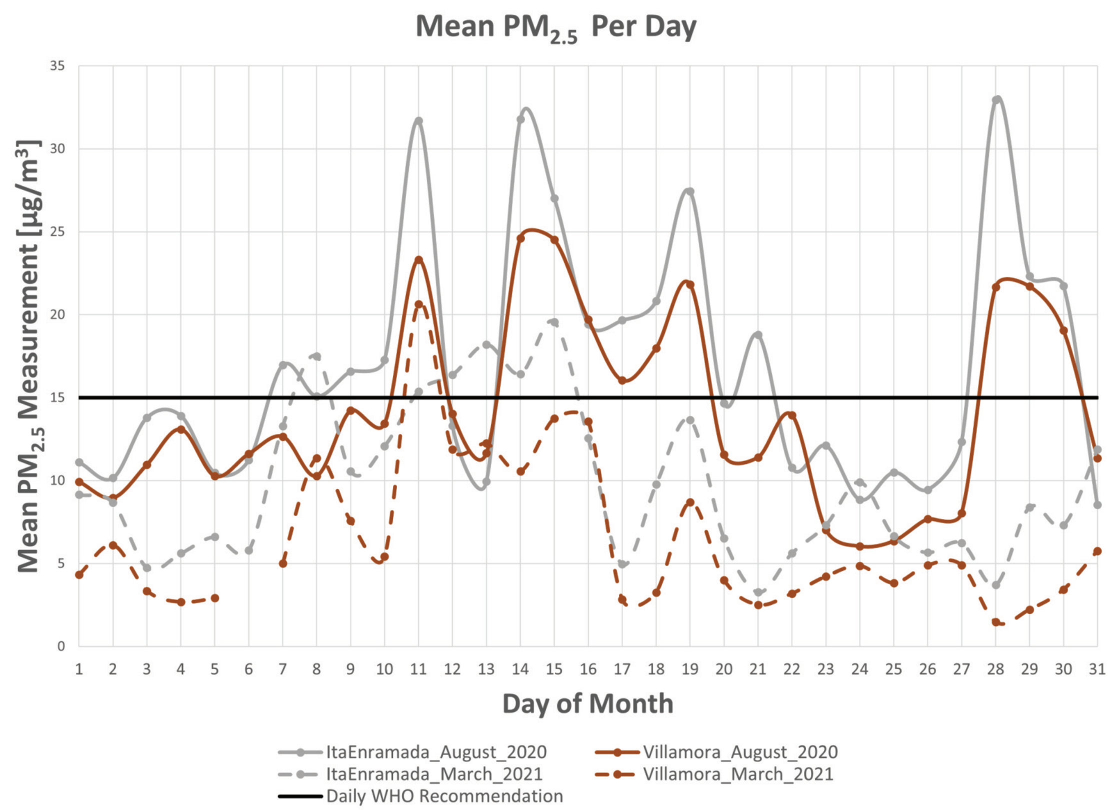

Figure 6. Sensor-measured daily $PM_{2.5}$ means for ItaEnramada and Villamora during August 2020 (fire season) and March 2021 (rainy season).[13]

Note: The black line shows the WHO's daily $PM_{2.5}$ recommended standard for reference.

concentrations tended to be higher during the night and in the morning. These elevated concentrations may result from morning inversions trapping pollution near the surface from local and regional source activity. By evaluating these temporal pollution trends, information can be gained on potential sources and meteorological influences on Asunción's air quality.

Climatic conditions also affected air quality in Asunción. Figure 6 shows average daily $PM_{2.5}$ concentrations for ItaEnramada and Villamora over one month during rainy (March) and dry (August) months in Asunción. These two sites were compared due to seasonal anthropogenic fires near the river adjacent to ItaEnramada, while Villamora represents typical residential areas with high population density and traffic emissions. Over both months, ItaEnramada's $PM_{2.5}$ concentrations were higher than Villamora's measurements. This may suggest ItaEnramada is impacted by local sources of $PM_{2.5}$ beyond just fires in the dry season, further highlighting the usefulness of ground-level sensors in understanding $PM_{2.5}$ at finer spatial resolutions. For both sites, the dry month concentrations were higher than measurements during the rainy month due to particulate removal by precipitation and minimal local or regional fires during the rainy season. Both locations experienced $PM_{2.5}$ measurements that exceeded the WHO recommended limit of 15 µg/m³. The variability in these locations' average daily $PM_{2.5}$ concentrations also suggests that even in a smaller city like Asunción (127.51 km²), seasonality, diurnal cycles, and anthropogenic activities can significantly influence $PM_{2.5}$ levels.[7]

Conclusion

The absence of air pollution monitors is a challenge when assessing $PM_{2.5}$ levels and trends for a region in order to identify public health concerns and develop air quality improvement strategies. However, this challenge can be mediated with the combination of satellite and ground-level air quality sensing. This article provides examples of how these approaches can be used to better understand $PM_{2.5}$ concentrations, as well as the temporal and spatial variability of these concentrations, using a case study for Asunción, Paraguay. Through this effort, exposures to $PM_{2.5}$ for Asunción's population can be estimated.

This case study can also provide insights about potential sources of local $PM_{2.5}$ air pollution, the impact of seasonal fires on air quality, and the potential localized differences in $PM_{2.5}$ emissions. Additional insights can be generated from this data concerning optimal siting for future air quality monitors in Asunción and the potential need to monitor other air pollutants beyond $PM_{2.5}$. In addition, the high sensor values highlight the need for reference, ground-level air quality monitoring to provide important quality assurance data for satellite measurement calibration, as well as accuracy and precision data for the sensor measurements rather than relying on manufacturer specifications. With quality assured satellite and sensor data, future analyses can provide more in-depth evaluations and comparisons of air quality data to identify and confirm trends in spatial and temporal pollution in Asunción and the impacts of local and regional pollution sources to develop effective air pollution control programs that protect public health. **em**

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Acknowledgment: The authors thank Karoline Barkjohn, Andrea Clements, and Vlad Isakov of the U.S. Environmental Protection Agency for technical reviews of the draft manuscript. The ground-level sensor data were provided by Aire Paraguay through Guillermo Pallarolas Rodríguez Alcalá. This study was conducted in 2020–2021 while Lauren Prox served as a volunteer with the U.S. Department of State's Greening Diplomacy Initiative. During this time, Dr. John Kerekes served as a Jefferson Science Fellow with the Greening Diplomacy Initiative at the U.S. Department of State, and he continues as a Senior Science Advisor. During this project, Dr. Richard Baldauf has continued serving as an Air Quality Fellow to the U.S. Embassy in Asunción, Paraguay.

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