Spatiotemporal Variations of $PM_{2.5}$ From Reference-Grade and Low-Cost Monitors in Rwanda

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Project Paper

I. Introduction

Air pollution was the second leading risk factor, after malnutrition, for premature death in Rwanda in 2017, including 1,220 estimated deaths due to ambient fine particulate matter ($PM_{2.5}$) alone (Health Effects Institute, 2019). Exposure to $PM_{2.5}$ is linked to a plethora of health problems such as lung cancer, heart disease, stroke, and diabetes. $PM_{2.5}$ can either be directly emitted into the atmosphere from anthropogenic or biogenic sources or formed through secondary chemical reactions. Beyond adverse impacts on human and ecological health, $PM_{2.5}$ (or aerosols) can scatter or absorb incoming solar radiation and thereby significantly affect our climate.

Rwanda is a small, densely populated, and landlocked country located just south of the equator in Africa—bordering Uganda, Tanzania, Burundi, and Democratic Republic of the Congo. The country experiences a tropical highland climate, but the topography is complex with rolling hills and volcanoes (950-4507 m elevation), driving the increase in annual mean precipitation from the east to west (800-1500 mm) through orographic lifting (Abimbola et al., 2017). Kigali is the capital and largest, central city in Rwanda, with a rapidly growing population of over one million people out of about 13 million people in Rwanda (Henninger, 2013).

Locally, emissions in Kigali largely come from old, poorly maintained mopeds, motorcycles, and other vehicles as well as from charcoal burning for cooking (Henninger, 2013; Subramanian et al., 2020). A recent study noted that air quality can be much worse along roads than at urban background locations and found that traffic restrictions on certain Sundays reduced $PM_{2.5}$, including black carbon, by 10-12 µg m^3 (Subramanian et al., 2020). Key businesses, residential districts, and government quarters are on ridgetops, while other people are forced to settle in valleys where pollution can be trapped in stagnant, stable meteorological conditions (Henninger, 2013).

In addition, pollution can be transported regionally from fires depending on the season and weather patterns. Rwanda's two dry seasons coincide with the northern and southern African biomass burning seasons, which are December-January-February and June-July-August, respectively (DeWitt et al., 2019). On the other hand, pollution transport distances are shorter in the two rainy seasons due to wet deposition and lower emissions. Unlike African countries to the north and west of Rwanda, dust from the Sahara Desert appears to negligibly influence Rwanda's air quality compared to biomass burning.

Despite the exceedingly high $PM_{2.5}$ levels in Africa relative to other parts of the world, there remains a paucity of reliable ground-level measurements, hindering air quality management. The average $PM_{2.5}$ monitor density in Africa, which has over 1.2 billion inhabitants, is 0.03 per million people, with many countries having zero monitors (Martin et al., 2019). One way to fill these data gaps is to utilize "low-cost" monitors that, because they are cheaper to purchase and maintain than reference-grade monitors, provide greater spatiotemporal coverage. However, these low-cost monitors simply use light scattering and tend to be less accurate due to sensitivity to temperature, relative humidity, particle concentration, and chemical composition (Hua et al., 2021). Therefore, we usually try to calibrate them with co-located reference-grade monitors.

The primary objective of this project was to analyze patterns in observed hourly, daily, seasonal, and overall mean $PM_{2.5}$ concentrations at urban and rural sites across Rwanda, as a case study of Africa. Although low-cost monitor data have considerable uncertainty, these additional measurements are expected to, nonetheless, provide valuable insights into how $PM_{2.5}$ varies in space and time beyond just one reference-grade monitoring site and year in Kigali. This short study represents another step towards understanding air pollution more completely in data-sparse Africa.

II. Data and Methods

I obtained raw hourly ground-level $PM_{2.5}$ data at a total of 18 monitoring sites in Rwanda from two sources: (1) AirNow Department of State and (2) Rwanda Environment Management Authority (REMA). AirNow provided data from February 2022–March 2023 for the reference-grade monitor (Teledyne T640) at the U.S. Embassy in Kigali. The estimated cost of the instrument is $20,000 plus additional costs for climate control, shelter fabrication, etc. ($50,000 total). REMA manages 17 real-time affordable multi-pollutant (RAMP) monitors from which $PM_{2.5}$ data from May-December 2021 were downloaded for this study. Eight RAMPs are located in Kigali, while nine RAMPs are located outside Kigali. SenSevere (now Sensit Technologies) manufactured the RAMPs and sold them for $3000 each plus the cost of paired MetOne neighborhood PM monitors (nephelometers), etc. (Subramanian et al., 2020). These RAMPs are "low-cost" relative to the Teledyne T640, but it is important to note that they may still be considered quite expensive in Africa. Here, the monitors are left uncalibrated because of the lack of co-located, co-occurring reference-grade monitoring, yet external correction factors exist that should be applied in future studies.

All the data processing and plotting was performed in Python. Though the reference-grade and low-cost monitor data did not overlap in time, I trimmed the reference-grade monitor data to the same time period (May 25–December 31) as the low-cost monitor data for consistency, just differing by year (2022 vs. 2021). The reference-grade monitor at the U.S. Embassy in Kigali had missing data, mainly during August-September and October-November 2022. I averaged hourly $PM_{2.5}$ by day, hour of day, day of week (not shown here), season, and over the entire time period (year). Using a background image of Rwanda from OpenStreetMap, I created plots of $PM_{2.5}$ at each of the 18 monitoring sites averaged over the entire time period as well as the dry and rainy seasons (not shown here). Dry seasons were defined as December-February and June-September, while rainy seasons were March-May and October-November.

III. Results and Discussion

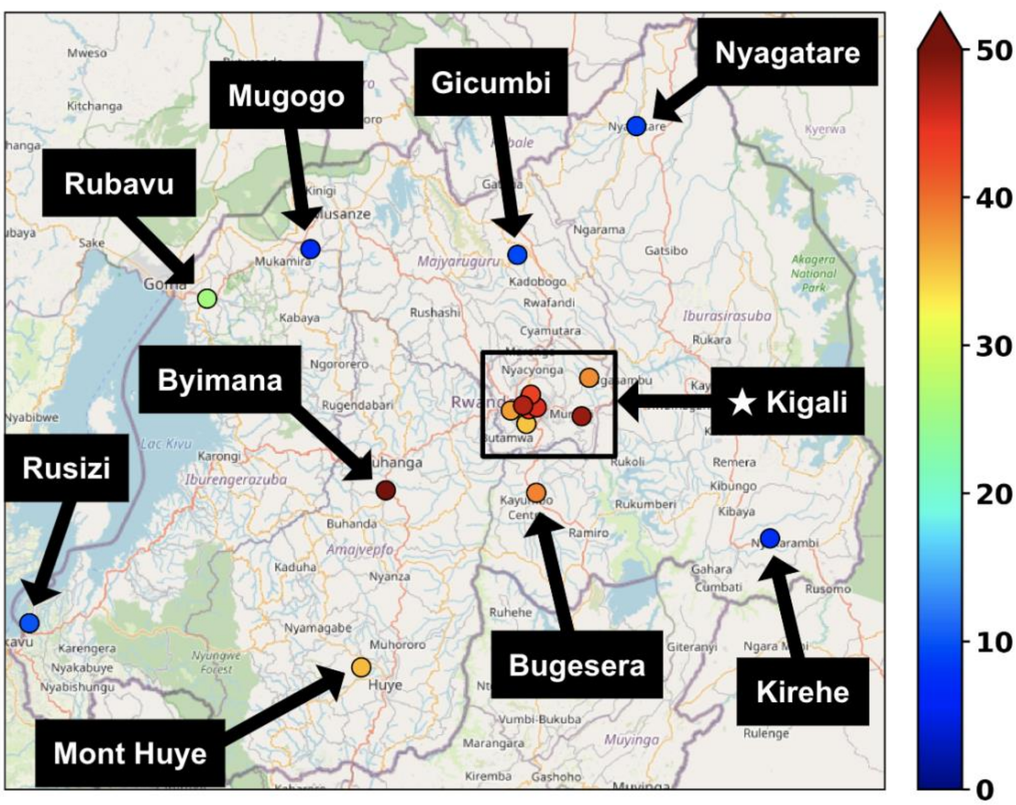

Figure 1. Overall mean $PM_{2.5}$ (averaged over May-December) at each of the 18 monitoring sites in Rwanda. Note that some of the points in Kigali are obscured or overlapping due to the map scale (source: OpenStreetMap).

As displayed in Figure 1, $PM_{2.5}$ was higher (red) over the entire time period in urban areas, namely Kigali, and lower (blue) in rural areas. The overall mean $PM_{2.5}$ from the reference-grade monitor at the U.S. Embassy in Kigali was 52 µg m^3, matching that reported in Subramanian et al. (2020). Assuming trivial differences in year and exact location, the low-cost monitors underestimated overall mean $PM_{2.5}$ by 5-17 µg m^3 compared to the reference-grade monitor. Interestingly, the highest overall mean $PM_{2.5}$ of 61 µg m^3 was not in Kigali; rather, it was at the Byimana site in close proximity to a road, which might indicate a major contribution from vehicles driving over the unpaved, dusty road. As for the lowest overall mean $PM_{2.5}$ of 7 µg m^3, at the Mugogo site, it makes sense that remote, mountainous areas (>2500 m elevation) had relatively clean air in the absence of fires. We may infer from the available data that local or urban emissions, including from transportation and wood or charcoal burning, had greater contributions to $PM_{2.5}$ than did regional or long-distance transport (controlling background concentrations) within Rwanda or from other countries.

In Figure 2, daily time series show that $PM_{2.5}$ consistently exceeded the guideline for 24-hour mean concentrations of 15 µg m^3, set by the World Health Organization (WHO), at all nine sites in Kigali and at four sites outside Kigali. In fact, $PM_{2.5}$ reached the “unhealthy” category (55-150 µg m^3), based on the U.S. air quality index, at these sites. This suggests that millions of people may be regularly exposed to poor ambient air quality in Rwanda. Of course, there was day-to-day variability due to changes in emissions and meteorological conditions such as wind, yet there seems to be agreement in longer-term, seasonal trends among the Kigali sites. The seasonal differences in $PM_{2.5}$ were more pronounced at the Rubavu and Mont Huye sites, where rain significantly removed pollutants. Alternatively, the sharp drop in $PM_{2.5}$ in the latter part of the year might be due to successful pollution reduction policies, though more data would be necessary to prove this. At five rural sites, the $PM_{2.5}$ was much lower, largely staying below the WHO guideline of 15 µg m^3. Seasonal variability at these sites was modest because $PM_{2.5}$ levels were consistently low. However, recall that low-cost monitors are sensitive to environmental conditions, for example, high humidity in rainy seasons that could cause overestimation of $PM_{2.5}$ (Hua et al., 2021). Another way to visualize daily mean $PM_{2.5}$ is through comparing distributions of $PM_{2.5}$ side by side in a violin plot (Figure 3). Across all sites in Rwanda, $PM_{2.5}$ was 38% higher on average in the dry seasons due to more biomass burning and lower in the rainy seasons due to more wet deposition.

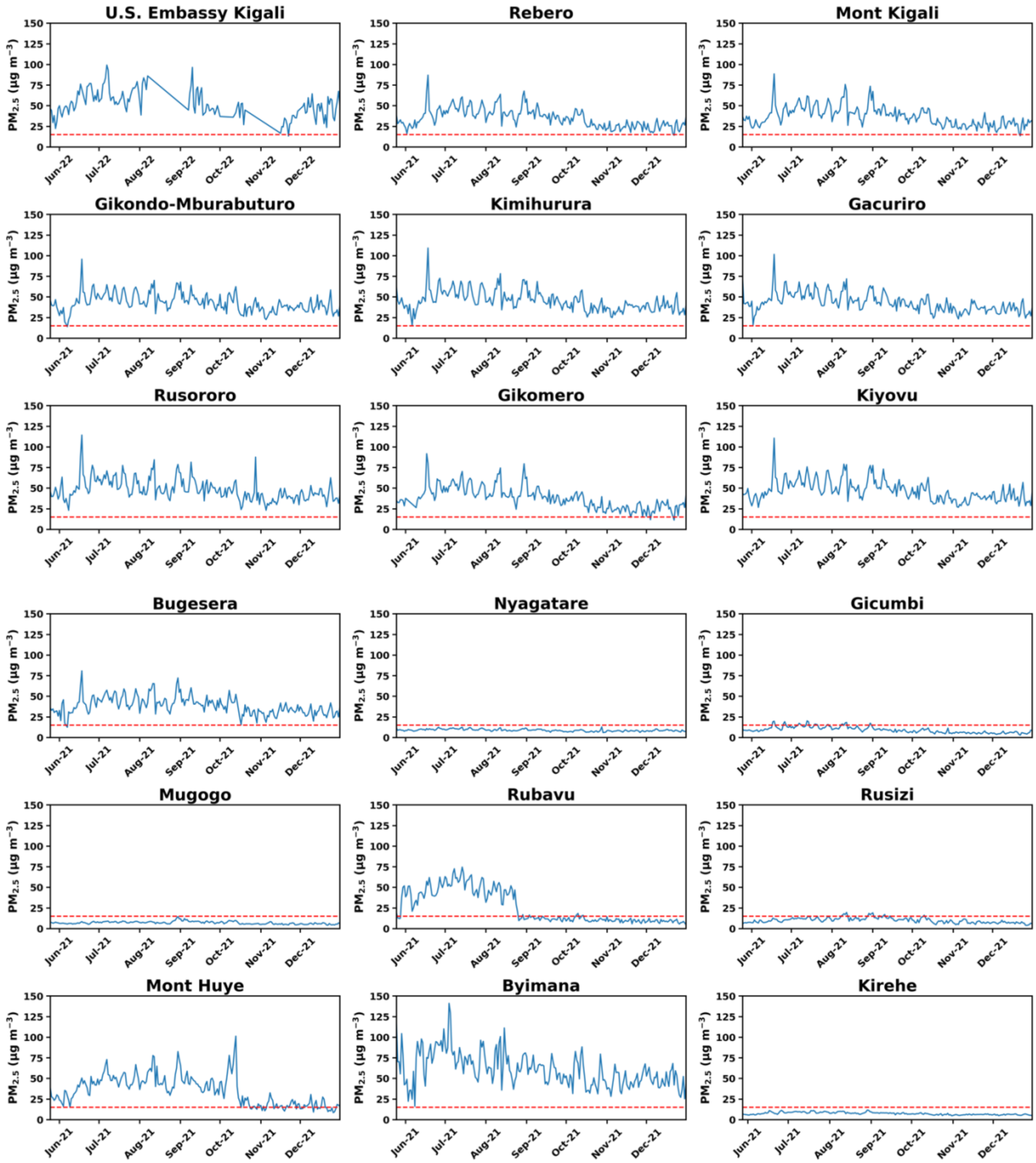

Figure 2. Daily mean $PM_{2.5}$ time series at each of the 18 monitoring sites in Rwanda. The top three rows of subplots are for sites in Kigali, while the bottom three rows of subplots are for sites outside Kigali. Red dotted lines denote the WHO guideline for 24-hour mean $PM_{2.5}$ of 15 µg m^3.

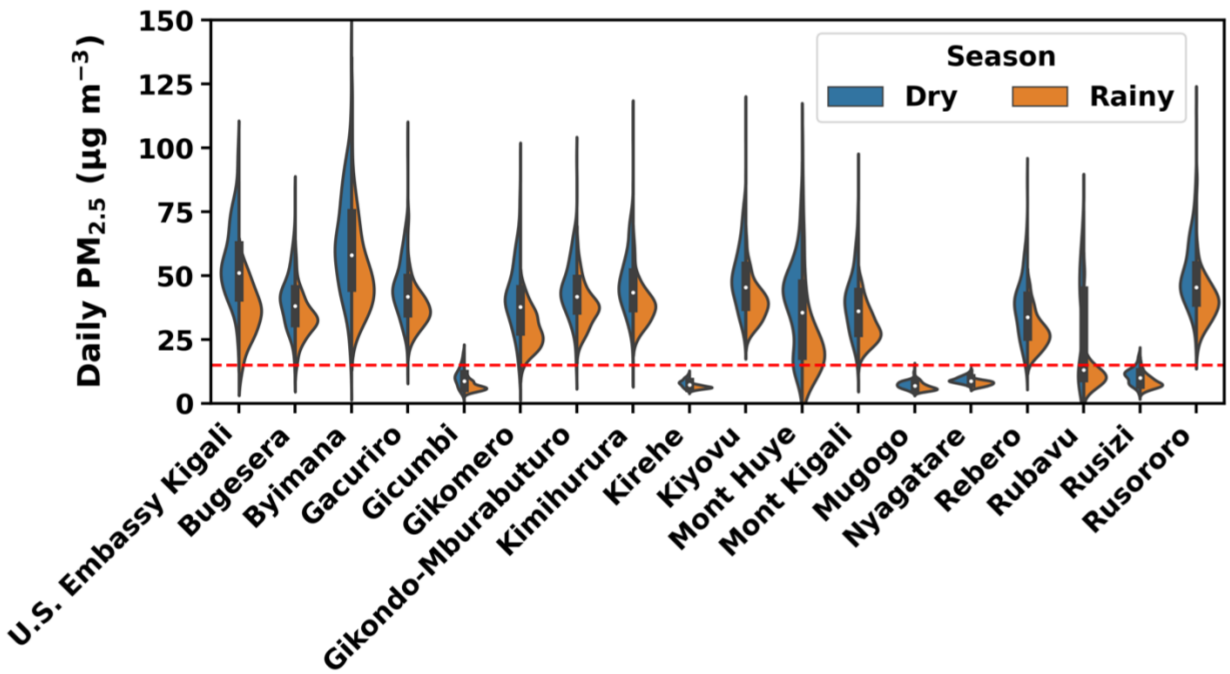

Figure 3. Violin plot of daily mean $PM_{2.5}$, featuring the standard box-and-whisker plot as well as a kernel density estimation of the underlying distribution, for all 18 monitoring sites. $PM_{2.5}$ was averaged over dry (blue) and rainy (orange) seasons. Again, the red dotted line is the WHO guideline for 24-hour mean $PM_{2.5}$ of 15 µg m^3.

Examining the typical diurnal cycle of $PM_{2.5}$ at each of the sites (Figure 4), $PM_{2.5}$ was generally higher in the night when the planetary boundary layer (PBL) was shallower and stable but lower in the day when the PBL was deeper and convective. Sunlight heats the surface which causes vertical mixing and dilution of the PBL. Five rural sites had $PM_{2.5}$ below 15 µg m^3 at all hours of day with little diurnal variation, again due to low concentrations or instrument sensitivity, whereas $PM_{2.5}$ always exceeded that value at the other 13 sites. Furthermore, there were morning and evening peaks in $PM_{2.5}$, likely due to rush-hour traffic. These peaks are more noticeable at 6-7 AM local time (LT) and 7-8 PM LT, more extreme in the evening (increase of up to about 70 µg m^3), at the Byimana and Rubavu sites. Therefore, instrument proximity to congested or dusty roads may significantly impact the data, demonstrating the need for hyperlocal air quality information with minimal data gaps to help reduce emissions and prevent exposure in specific peak pollution times and areas.

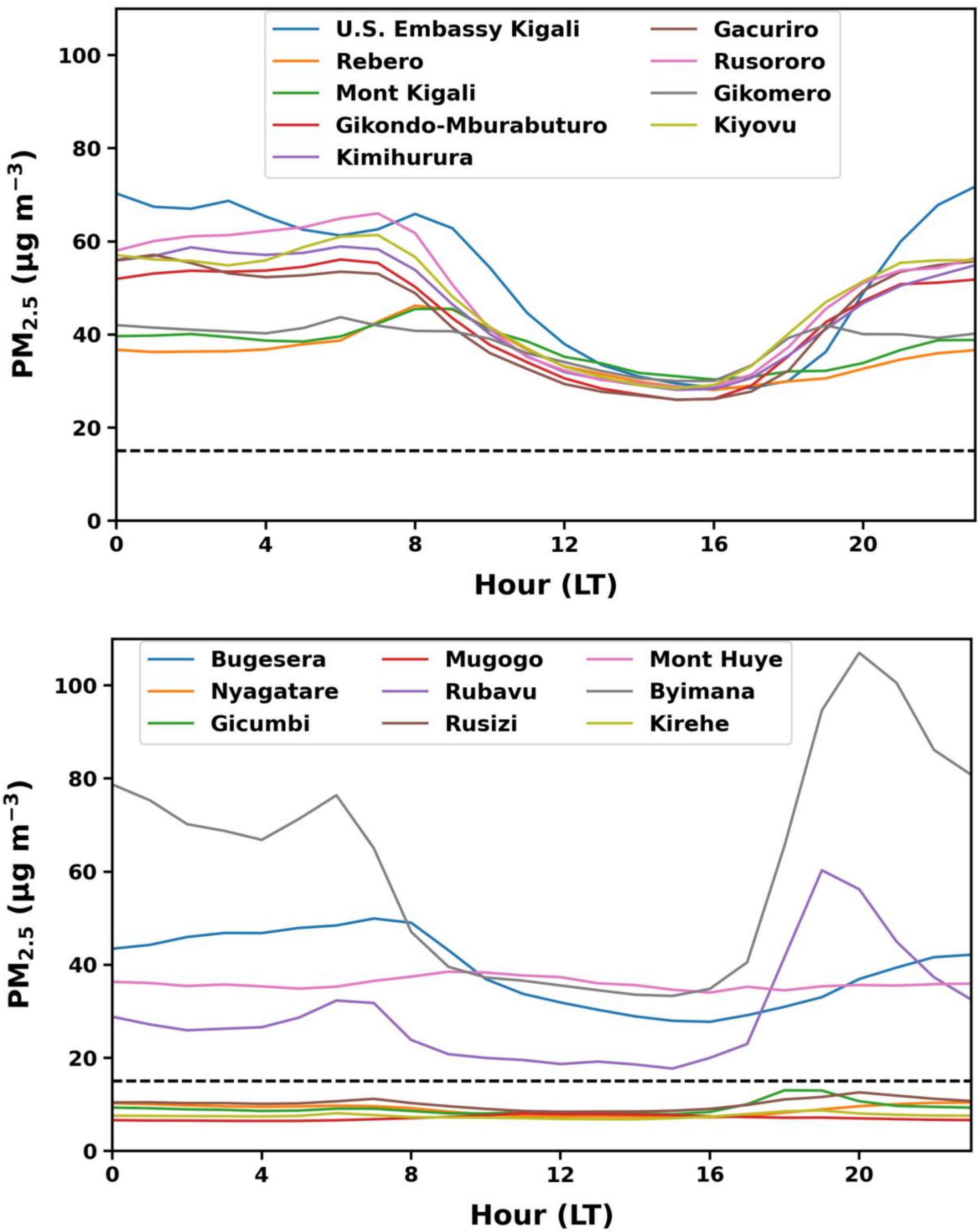

Figure 4. Average diurnal cycle of $PM_{2.5}$ at all the monitoring sites in Kigali (top subplot) and outside Kigali (bottom subplot). LT is local time, and the black dotted line is the WHO guideline for 24-hour mean $PM_{2.5}$ of 15 µg m^3.

IV. Conclusions

This project highlights the value of using low-cost monitors to identify general spatiotemporal patterns in Rwanda and elsewhere, even if the data is less accurate than those from reference-grade monitors. At most of the sites throughout Rwanda, daily mean $PM_{2.5}$ exceeded the WHO guideline (>15 µg m^3) and reached unhealthy levels (>55 µg m^3). The exceptions were five remote sites with consistently low $PM_{2.5}$ levels below the WHO guideline, but most people reside in urban, polluted areas and thus are more likely to experience adverse health impacts. As expected, air quality was particularly poor in the largest city of Kigali (higher local emissions), during the night (shallower PBL), and during the dry seasons (more biomass burning).

Given that the low-cost monitors underestimated $PM_{2.5}$ relative to the reference-grade monitor in Kigali, we may find that pollution was even worse at these sites if the data are corrected. However, overestimation of $PM_{2.5}$ might occur, for instance, depending on humidity and aerosol levels. In addition to calibration, more $PM_{2.5}$ monitors need to be deployed throughout Africa in the future to fill the widespread data gaps. Ideally, we will understand air pollution more fully through an integrated framework (Martin et al., 2019). I aim to continue this work by leveraging not only reference-grade and low-cost monitors in Africa but also satellite remote sensing, GEOS-Chem chemical transport modeling, and machine learning to estimate $PM_{2.5}$ at high spatiotemporal resolution. The resulting products will hopefully allow us to better safeguard human and ecological health and understand the air quality-climate relationship.

V. References

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