Modelled impact of precipitation, wind factors, and tourism presence on particulate matter (PM) concentration in atmosphere surrounding Marrakech, Morocco

word count: 1974

**Introduction**

Ambient air pollution in Morocco causes thousands of premature deaths every year (Croitoru and Saraf, 2017) and has an estimated average cost on the economy of US$1.148 billion annually – 1.05% of the country’s GDP, (World Bank; 2020). Compared to other large cities in Morocco, Marrakech is located further south and despite being separated by the Sahara Desert by the Atlas Mountains, the atmosphere is still rich in dust particles all year round (Saidi, Valari & Ouarzazi, 2023). The negative effect of dust particles on health is exacerbated by an energy market highly dependent on solid fuels – wood, coal, and petroleum derived products (Saidi, Valari & Ouarzazi, 2023). Annual mean fine particulate matter PM2.5 and PM10 concentrations in Marrakech are reported to exceed WHO guidelines by over 2 or 3-fold on average (World Health Organization, 2016). These worrying statistics are relatively common for LMICs throughout the Middle East and North Africa, though Morocco’s government is slowly shifting to renewable energy sources to reduce sources of pollution and create a more independent economy (Saidi, Valari, & Ouarzazi, 2023). Since 2010, wind power has expanded throughout the country, contributing over 1 GW (Dettner & Blohm, 2021). Despite this the Moroccan Energy Ministry’s (MEMEE) *Strategie Energetique National – Horizon 2030*, published in 2009 does not exclude coal-fired power plants due to there being many affordable coal suppliers around the world which ensures energy security for Morocco as the country develops renewable energy infrastructure (Dettner & Blohm, 2021). Tackling air pollution contributes to the realisation of key UN sustainable development goals (SDGs), in particular SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 11 (Sustainable Cities and Communities).

These statistics drive the need to better understand the relationships of PM2.5 and PM10 presence in relation to variables such as anthropogenic activity – e.g. vehicular activity, construction works, mining; along with other environmental variables – e.g. precipitation, wind speed and wind direction, presence of vegetation (such as through NDVI). Combining the interactions these different variables may have on air quality becomes ever more prevalent with changing climates and societal conditions that may lead to further health crises (IPCC, 2023). Studies in Seoul, Korea have shown the ability of precipitation to washout PM10 concentrations from the air (Kim et al., 2014). While wind speed and direction were shown in Hong Kong to affect which pollutants arrived and were blown away from the city (Cheng-al & Lam-al, 1998). When it comes to anthropogenic factors, tourism plays an important role in Morocco’s economy. In 2022, despite not having fully recovered by then from the Covid-19 pandemic, the number of tourists was approximately 10.9 million, with a spending of over US$ 9 billion making up 6.9% of the Gross National Product (GNP) (worlddata.info, 2023). In Southeast Asia, tourism has shown to be negatively or positively correlated with air pollution depending on each country’s approach to forming sustainable economic growth and development pathways (Azam, Alam, & Hafeez., 2018).

Investigating the relationships between both anthropogenic and environmental variables with high accuracy can be a challenge (Saidi, Valari & Ouarzazi, 2023), especially when attempting to do so in low and middle-income countries (LMIC) where there may not be enough public resources and monitoring systems in place (Mazzeo et al., 2022). While developing resources to fund the development of public monitoring schemes is essential to better investigate impacts at a high resolution, remote sensing data such as CAMS global atmospheric composition forecasts can be used to make rough investigations of correlations between various atmospheric constituents.

This report investigates the presence of two potential air pollutants PM2.5 and PM10 in Marrakech, Morocco and compares them with precipitation, wind direction, and wind speed data from the Copernicus Atmosphere Monitoring Service (CAMS) global atmospheric composition forecasts, 2018-2022 (ECMWF, 2025). Tourism annual statistics are also implemented into the statistical analysis to see if increased human activity on certain years could be influencing PM presence in the atmosphere and are compared with the impact from Covid-19 lockdown in Morocco. An air quality monitoring station in Rue de Temple with PM data from 2024-2025 is compared with the CAMS data to assess whether remote sensed data can be an effective proxy when monitoring stations are lacking.

**Methodology**

*Location:*

A map with red lines

AI-generated content may be incorrect.A satellite view of a map of the sahara

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*Map 1: Marrakech districts in Morocco sheltered from the Sahara Desert by the Atlas Mountains to the SE.*

*Data:*

PM, Precipitation, and wind data was collected from CAMS as .grib files for the years 2018-2022 as the tourism data in Morocco only extended to 2022 (worlddata.info). Recorded daily data from CAMS is averaged from times 00:00 and 12:00 to better represent daily variation.

*Statistical analysis:*

Plotting different graphs to look for visual trends and relationships is a useful strategy for finding intuitive patterns in data. LOWESS curves are implemented prioritize the visualisation of general trends with different resolutions (based on the optimal data fraction breadth selected for calculation of LOWESS curves to visualise the results clearly).

Along with visual displaying of trends, Pearson correlation was used for determining the correlation between continuous independent variables (wind speed and precipitation) and PM concentration. The datasets were also shifted a day earlier to determine whether there was a lagged effect that increased the correlation between PM and continuous independent variables. Random Forest analyses were also done for the CAMS variables and temporality (i.e. month of the year) to determine whether precipitation, wind, or month of the year contributed in non-linear fashion to predicting accurately the PM2.5 and PM10 values.

Since tourism data was only found at an annual-based resolution, the tourism datasets were tested along with binned wind direction (binning: N, NE, E, SE, S, SW, W, NW) for correlation through a Ranked Pearson Correlation test.

**Results**

*Visual Comparison:*

A graph of blue and orange lines

AI-generated content may be incorrect.*1.1 PM2.5 and PM10 and Covid-19 events in Morocco*

Figure 1: particulate matter concentrations in Marrakech over time from CAMS remote sensing data

When comparing the behaviour of PM10 and PM2.5 (Figure 1) we can see that PM10 consistently has a higher concentration on average, with a significant prolonged divergence of concentrations between the two particle sizes mid-2019 which falls back to previous proximate synchrony before 2021. PM2.5 concentrations remain much less volatile throughout the studied time period. It should be noted that the beginning of lock down in Morocco correlates with a relative drop in PM presence, while the uplifting of stringent travel rules is followed by a sharp upward spike in PM presence. The fraction of the dataset used for estimating PM concentrations in the LOWESS trend lines was 0.01 approximating to 18 days around each time point (a smaller number generalizes less).

*1.2 Precipitation*

A graph of a graph

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Figure 2: Mean precipitation values for each month with a LOWESS trend to show the general trend of the monthly data. Lower error bars omitted as every month had a significant number of days with 0 rainfall.

While the PM data did not have visibly noticeable seasonal trends, precipitation (Figure 2) shows to have a tendency to be lowest during summer. This indicates a likelihood that PM and precipitation are not correlated. LOWESS trend lines were set to 10% of the data at each point, meaning that the precipitation value for each month was calculated from the surrounding 6 months (a higher fraction than the PM graph to show more generalized trends).

A graph of a wave

AI-generated content may be incorrect.*1.3 Wind speed and wind direction*

Wind direction (Figure 3) shows to be strongly seasonal, with higher wind speeds during summer and lower wind speeds during winter. This does not match the behaviour of PM presence. The LOWESS fraction used was 0.1 following the same proportion of the precipitation data (Figure 2)

Figure 3: Daily wind speed from 2018 to end of 2022A calendar of the months

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Figure Group 4: Boxplot (above) shows PM concentrations for each month over 4 years. To be compared with monthly wind roses (right) that shows frequency of wind directions (length) and temporal composition of wind speed (colour) for each month. Empty wind roses represent little wind in highly variable directions for the particular month.

Wind speed and direction show to have no clear correlation with PM through visual comparison.

A group of blue bars

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Figure 6: Tourism related annual statistics

Although tourism annual statistics do not show visible correlations with PM concentration in Marrakech, it is clear that the Covid-19 lockdown has had a clear effect on both tourism statistics and PM concentrations even if just briefly for the latter.

*2.1 Statistical Analysis Results:*

For both PM2.5 and PM10, the only independent variable that had moderate or high Pearson Correlation values (0.3 < |p|) was wind speed with a negative correlation (-0.48 and -0.38 respectively) meaning that when there was more wind, PM concentration decreased. Creating a lag in wind and precipitation data did not contribute to increasing correlation values and in fact slowly decreased the correlation. Despite lack of significant correlation, PM2.5 generally showed to be more responsive to environmental and anthropogenic factors than PM10 throughout.

A graph of a line and a red line

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Figure 7: Spearman correlation coefficient plotted with PM data against wind speed

Random Forest runs showed similar correlations when it came to the strength of each independent variable with wind speed dominating in feature importance with a large Random Forest Mean Squared Error of 81.74 for PM2.5 and 80.54 for PM10. This also indicates that the variables studied do not likely have a significant non-linear relationship with PM presence.

Ranked Pearson Correlation values on the other hand showed no moderate or high correlations for number of tourists, receipts, percentage of GNP and wind direction indicating that there are no strong relationships between such factors and PM concentrations.

**Discussion**

Modelling environmental interactions is difficult to do in half-measures. The dynamic system with both anthropogenic and environmental factors constantly varying and depending on spatial and temporal seasonal effects makes this area of research as complex as it is important. This report has investigated 4 related anthropogenic factors, number of tourists, receipts, and % contribution of those factors on GNP. These anthropogenic factors led to no significant correlations with PM concentrations. While wind direction and precipitation had no more of a significant effect than anthropogenic factors studied, wind speed showed to be moderately correlated with both PM2.5 and PM10 concentration in the atmosphere. Covid-19 also showed to have a visible though brief impact on PM2.5 and PM10

Wind speed’s significant correlation with PM concentrations has to do with the ability for wind to wash away stagnant suspended particles and replacing the atmosphere’s air from other regions less effected by pollution.

The combination of different possible factors in this report, attempted to capture changes over a large time period to better visualise seasonal cycles and their impacts on PM concentration. Clear needs for improvement in further studies is higher resolution of tourism data to show trends from month to month or day to day, as well as other data such as traffic activity or vegetation productivity to monitor other sources of potential PM. Using remote sensing data has the benefit of making approximations easily accessible, however more on-the-ground monitoring would help provide accuracy and also better calibrate the predictions made by remote sensing services for cities and their air quality levels.

Reducing health risks such as air pollution is of dire necessity world-wide. With LMICs having a slower transition to renewable energy and generally weaker health care systems, they are of the most vulnerable countries to weak infrastructure in this field. As clearly seen (Figure 1), PM concentrations can at times exceed 10 times the recommended WHO guidelines in Marrakech, showing the urgency of the issue at hand.

The future of PM concentrations in Marrakech is very difficult to predict, but creating infrastructure we know can help reduce harmful PM presence. Producing more means to study the dynamics of pollutants can help save lives in the long run and can play a part in developing sustainable economies, populations, and environments with immediate benefits from mitigative or predictive structures developed.

**Data analysis:**All data analysis done for this report can be found in the GitHub repository: <https://github.com/Arkaned/Air-Pollution-Report.git>

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