The Contribution of Large-scale Atmospheric Patterns to PM₁₀ Pollution: The New Saharan Oscillation Index

Kenza Khomsi^{1,2*}, Houda Najmi¹, Youssef Chelhaoui¹, Zineb Souhaili²

¹ *Direction de la Météorologie Nationale, Boulevard Mohamed Tayeb Naciri, Hay Hassani, B.P. 8106 Oasis-Casablanca, Morocco*

² *Laboratory of Drugs Science, Biomedical and Biotechnological Research. Faculty of Medicine and Pharmacy, Hassan II University, Ain Chock. Casablanca, P.B. 5696, Morocco*

ABSTRACT

PM₁₀, an urban air pollutant that originates from both natural and anthropogenic sources (desert dust and industrial and traffic emissions), reduces visibility and threatens human health, particularly in large cities.

Casablanca, which exhibits the highest urbanization rate and population density in Morocco, possesses a concentration of industrial units as well as a large vehicle fleet. Marrakech, another of the most populated cities in the country, has also witnessed an increased rate of motorization during the recent years.

The primary objective of this study was to evaluate the relationship between the atmospheric circulation and the PM₁₀ concentrations in Casablanca and Marrakech (based on daily measurements from 2013 to 2016). First, we assessed the correlations between the concentrations and the climate indexes (the North Atlantic Oscillation [NAO] and the Mediterranean Oscillation [MO]). Then, we characterized the contribution of large-scale atmospheric patterns related to extreme PM₁₀ events. Finally, we created the Saharan Oscillation Index (SaOI), a climate index for characterizing the oscillation in the country's southern desert, between the Saharan depression and the Azores High, and calculated its time series.

Our results elucidate the relationship between the MO and the average PM₁₀ concentrations, demonstrating that particulate pollution in the study area is partly induced by a northeasterly to southwesterly continental flow that is triggered by the Saharan trough and influenced by the high-pressure area in the north. The significant statistical correlations, mainly found in winter, confirm the relationships between the Saharan Oscillation Index, the average PM₁₀ concentrations and the MO and NAO indexes—and thus the applicability of the SaOI—during this season.

Keywords: Particulate matter (PM₁₀); Correlation; Saharan depression; Climate index; Saharan Oscillation Index (SaOI); Air quality.

INTRODUCTION

Nowadays, air pollution and climate change are the greatest atmospheric challenges for societies, and they will continue in future decades. These environmental issues are highly connected, mainly through atmospheric processes and meteorological conditions (von Schneidemesser *et al.*, 2015; Kusumaningtyas *et al.*, 2018; Sfică *et al.*, 2018).

Air pollution is derived from local pollution sources but also affected by large-scale movement of air masses that contribute to regional background pollution and air pollution episodes. The World Health Organization (WHO) has estimated that ambient air pollution is responsible for

7,000,000 premature deaths per year in the world (WHO, 2014); 500,000 individuals are affected by premature death every year because of exposure to suspended particulate matter (PM) in ambient air (Alves *et al.*, 2014).

PM is one of the main urban air pollutants (Molina *et al.*, 2017; Hsu and Cheng, 2019), it is a mixture of particles with different chemical composition, shape and size (Khaefi *et al.*, 2017; Cheng and Wang-Li, 2019) and attributed to several natural and artificial sources (Gugamsetty *et al.*, 2012; Guo, 2018). When in high concentrations, the PM has significant impacts on the human health, well-being and environment. It has high potential to be accumulated in the human respiratory system and causes cardiopulmonary diseases and lung cancer (An *et al.*, 2018; Hopke *et al.*, 2018; Kirrane *et al.*, 2019; Li *et al.*, 2019). PM₁₀ is the PM type with aerodynamic diameter less than 10 micrometers, it is inhalable and has the capacity to alter the human respiratory capabilities. Moreover, it can cause the decrease

* Corresponding author.

E-mail address: k.khomsi@gmail.com

of visibility, smoke, haze, and smog (Agustine *et al.*, 2018).

Weather conditions and meteorological factors play a crucial role in air pollution, mainly by PM₁₀, and many previous studies have described the relationship between that pollutant and weather parameters (Tecer *et al.*, 2008; Czernecki *et al.*, 2016; Sfică *et al.*, 2018). Furthermore, some particular synoptic patterns are strictly related to dangerous PM₁₀ incidents that generally coincide with stagnant conditions induced by high relative humidity, thermal inversions, and low wind speeds, that reduce the ventilation and decrease the dispersion of the atmospheric components near to the surface (Pateraki *et al.*, 2012; Hsu and Cheng, 2019; Toro *et al.*, 2019).

In Morocco, air pollution is responsible for more than 13,000 deaths each year. This represents about 7% of all deaths and is thus the 8th largest mortality risk factor. More than 12,000 deaths are attributable to fine particles (IHME, 2018). The country has started to monitor air quality since 1997 in an effort to assess air quality, the risk of its alteration on human, vegetation, and climate and recognize the need to improve air quality and control emissions. Today in Morocco, PM₁₀ is being monitored in 15 cities using automated ground-based instruments.

Casablanca and Marrakech are two large metropolitan cities in Morocco with various sources of pollution by PM₁₀. The few studies already led on particle pollution in these two cities have mainly focused on assessing air data according to standard limits (Croitoru and Sarraf, 2017; Inchaouh and Tahiri, 2017; Inchaouh *et al.*, 2017, 2018).

The goal of this study is to evaluate the concentrations of PM₁₀ and characterize their relationship with large-scale atmospheric circulation through assessing their statistical correlations with the North Atlantic Oscillation (NAO) and the Mediterranean Oscillation (MO) indexes. In fact, for the Mediterranean region to which Morocco belongs, the path that cyclones take usually depends on synoptic-scale atmospheric patterns, connected to NAO and MO climate indexes. Numerous studies have revealed that these connections play a significant role in the determination of moisture transport in the region (Baltacı *et al.*, 2017; Drumond *et al.*, 2017; Şahin *et al.*, 2018). Also it has been found that both indexes impact the climate regime in Morocco (Khomsı *et al.*, 2016). This work is mainly about understanding how does weather contribute to the occurrence of particle pollution, it brings new insights on how the climate may affect trends and levels of PM₁₀ and will serve as a reference to evaluate the current air quality at the country-level scale. Also, it is a first step to identify PM₁₀ sources and distinguish contributions from local emissions and climate-induced fine particles, when necessary data is available. It will be a useful tool in the future to undertake appropriate actions against pollution by PM₁₀ and to develop pollution mitigation strategies.

In this paper, we describe the area of study, the methods used and we elaborate on the data acquisition. In Section 3, we first present the trends in PM₁₀ averages and extremes, we show PM₁₀ seasonal correlations with NAO and MO indexes and we identify and analyze synoptic patterns behind the occurrence of PM₁₀ extremes. Finally, we suggest the elaboration of a new climate index, the Saharan Oscillation

Index (SaOI), and assess its relationship with PM₁₀, NAO and MO indexes.

MATERIALS AND METHODS

The Study Area

Morocco is the country located in the extreme northwest of Africa (Fig. 1). Because of its location in the southern part of the Mediterranean region, the state is considered among the most vulnerable countries with regard to climate variability, particularly likely increased frequencies in extreme climate events (Khomsı, 2013; Filahi *et al.*, 2015; Khomsı *et al.*, 2016; Filahi *et al.*, 2017; Kamal *et al.*, 2018; Khomsı *et al.*, 2018) and accordingly extreme related pollution episodes.

Casablanca and Marrakech are the first and the fourth most populous cities in Morocco with more than 3,000,000 and 900,000 residents, respectively, as reported by the website of World Population Review (<https://worldpopulationreview.com/>). Casablanca is a coastal city located in the central western part of the country bordering the Atlantic Ocean (Fig. 1). It is the largest city in the Maghreb, as well as one of the most important cities in Africa, both economically and demographically. Marrakech is a major city of the Kingdom of Morocco; it is the capital city of the mid-southwestern region of Marrakech-Safi and is an inland city located to the north of the foothills of the snow-capped Atlas Mountains (Fig. 1). Casablanca and Marrakech were chosen as the urban study area where serious pollution concerns may be met, especially with the important population rate increase that reaches 11% in Casablanca and 12% in Marrakech between 2004 and 2014.

PM₁₀ Data

Daily mean data of PM₁₀ concentrations (in $\mu\text{g m}^{-3}$) were collected from thirteen air quality stations, ten in Casablanca and three in Marrakech (Fig. 1). These stations are technically managed by the National Weather Service. Before being available, the collected data underwent quality control in accordance with the rules and the recommendations from the Agency for the Environment and Energy Management (Kleinpeter *et al.*, 2003). For the purpose of this work, PM₁₀ spatial averages from the measuring stations in each city are used to represent the city. In Morocco, the air quality network is not old and the temporal coverage of available data is limited, therefore it was difficult to retrieve a long data sample. This study was performed on a daily basis for the period between 2013 and 2016 which may not be sufficient to obtain significant statistics yet it is the most appropriate period allowed by the available data. The analysis was presented on a seasonal basis in order to examine the seasonal variability in the obtained results.

Atmospheric Circulation Indexes

The centers of pressure for the NAO are located in the Atlantic Ocean (Ambaum *et al.*, 2001). This connection consists of a north-south dipole of the sea-level pressure (SLP) anomalies, one centered over Iceland and the other over Azores.

The MO was first suggested by Conte *et al.* (1989). It was

Fig. 1. (a) Location of Morocco in Africa, (b) location of the cities of Casablanca and Marrakech in Morocco, (c) air quality stations in the city of Casablanca, (d) air quality stations in the city of Marrakech.

defined as an oscillation between the east and the west of the Mediterranean Basin. According to the authors, this oscillation is the consequence of the behavior of the atmospheric dipole at the 500 hPa level between Algiers (36.4°N, 3.1°E) and Cairo (30.1°N, 31.4°E). The same model was applied by Douguédroit (1995) using SLP.

The annual data of the NAO and MO indexes were gathered from the website of the Climatic Research Unit (CRU; <http://www.cru.uea.ac.uk/cru/data>) and used in order to study the link between these two atmospheric modes and

the seasonal evolution of daily PM₁₀ averages between 2013 and 2016.

Sea-level Pressure Data

Daily data were used in order to retrace SLP patterns related to the identified PM₁₀ seasonal extreme events. This will help to associate the flows over the studied areas with extreme particle pollution conditions.

The SLP data were provided by the ERA5 reanalysis. ERA5 is the latest climate reanalysis data generated by the

European Centre for Medium-Range Weather Forecasts (ECMWF). Data contain hourly data on diverse atmospheric and land-surface parameters on 37 pressure levels. ERA5 data are accessible in the Climate Data Store (CDS; <https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset>) on unvarying latitude-longitude grids at $0.25^\circ \times 0.25^\circ$ resolution.

Methods

To identify extreme events in PM_{10} , the overall and seasonal 95th percentiles computed across the whole time period were used as thresholds. The 95th percentile is widely employed and recommended for climate and related application studies by the STATistical and Regional dynamical Downscaling of EXtremes for European regions (STARDEX; <http://www.cru.uea.ac.uk/projects/stardex/>) and the Expert Team on Climate Change Detection and Indices (ETCCDI; <http://cccma.seos.uvic.ca/ETCCDI/>) projects. Annual and seasonal datasets of mean daily PM_{10} recorded between 2013 and 2016 were compared to the calculated overall and seasonal thresholds, respectively. Thus, an extreme PM_{10} event is defined as a day that recorded an average PM_{10} greater than or equal to the 95th percentile.

The magnitudes of trends in time series were analyzed using the non-parametric approach proposed by Theil (1992) and Sen (1968) for univariate time series. This method implies the preparation of the ordinal time points and the calculation of the slopes for all the pairs and then the computing of the median of the calculated slopes as an estimate of the general slope. Sen's slope is widely used for the estimation of trends' magnitudes in climate series, given its robustness against outliers (Kamruzzaman *et al.*, 2016; Almeida *et al.*, 2017; Byakatonda *et al.*, 2018; Kahsay *et al.*, 2018). The statistical significance of the obtained trends is tested using the modified Mann-Kendall test proposed by Hamed and Ramachandra Rao (1998) for autocorrelated time series. The test is performed at a significance level of 5%.

Correlations between time series were estimated employing the Spearman coefficient. This statistical coefficient is used to measure the strength of the association between two variables and is widely used in climate studies (Mendez-Lazaro *et al.*, 2014; Hänsel *et al.*, 2015).

RESULTS AND DISCUSSION

Trends in Average PM_{10} , Thresholds and Frequencies of Extreme PM_{10} Events

Figs. 2 and 3 show respectively the evolution of annual and seasonal average PM_{10} and extreme PM_{10} events, Fig. 4 presents overall and seasonal PM_{10} thresholds for extreme events in the studied area between 2013 and 2016. Results show that the city of Casablanca has recorded more important annual PM_{10} averages in comparison with the city of Marrakech. The same finding appears for autumn, winter and spring. In summer, Marrakech has recorded more important averages in the last three years. Marrakech is already found to register more important PM_{10} concentrations in the summers between 2009 and 2012 (Inchaouh *et al.*, 2017). Concerning extreme events, observed frequencies

Fig. 2. Evolution of annual PM_{10} averages and extreme events.

are of the same order in both cities in winter and summer. Extreme event thresholds are more important in Casablanca than in Marrakech in all seasons but summer, they are more important in winter and they far exceed the WHO guideline level of $20 \mu\text{g m}^{-3}$ (WHO, 2006). This finding is in agreement with the previous studies of Croitoru and Sarraf (2017) and Inchaouh *et al.* (2017, 2018) where it is shown that PM_{10} concentrations in Casablanca and Marrakech exceed the cited WHO guideline level. The year 2014 was with fewer extreme events in both cities. A previous study on heat waves, in the same study area has shown that the year 2014 has recorded the lowest maximum temperature and frequency of hot events (Khomsı *et al.*, 2018). This may highlight the contribution of high recorded temperature to the occurrence of PM_{10} episodes as found by other previous studies (Analitis *et al.*, 2018; Kalisa *et al.*, 2018; Kliengchuay *et al.*, 2018; Egberts *et al.*, 2019). According to the data collected and the statistical approach used, the magnitudes of most studied trends in PM_{10} averages and extreme events are positive, but not statistically significant. This may be due to the short period of data availability that served for the present study.

Climate Indexes and PM_{10} Averages

The relationship between climate indexes and PM_{10} averages in Casablanca and Marrakech was assessed through the Spearman coefficient of correlation. Annual and seasonal results are shown in Fig. 5 and Table 1, respectively. Relationship between annual climate indexes and PM_{10} averages is confirmed and is stronger with the MO index for both cities. Seasonal data show that PM_{10} /NAO correlation is significant in autumn; meanwhile PM_{10} and MO keep to be correlated throughout the four seasons. Stronger PM_{10} /MO correlations were observed in the cold season (autumn and winter). When comparing both cities, coefficients of correlation are of the same order. The positive, moderate and significant correlation between MO index and PM_{10} averages during the cold season highlight the influence of anticyclonic conditions occurring in the northern Mediterranean coasts of Morocco, on PM_{10} concentrations over the studied area. This influence weakens but persists

Fig. 3. Evolution of seasonal PM₁₀ averages and extreme events: (a) autumn, (b) winter, (c) spring, (d) summer.

Fig. 4. Overall and seasonal PM₁₀ thresholds for PM₁₀ extreme events.

during the warm season (spring and summer). In autumn, NAO index fed through the anticyclonic conditions in the Atlantic on the west of Morocco maintains a weak impact on studied PM₁₀ concentrations. Anticyclonic settings are generally related to stagnation conditions that disadvantage dispersion and foster PM₁₀ concentrations. These findings are confirmed by the previous results of Pateraki *et al.* (2012), Hsu and Cheng (2019) and Toro *et al.* (2019), that have proved the interactions between anticyclonic conditions

and PM₁₀ high concentrations in the Mediterranean area, Taiwan and Chile, respectively. These interactions will be better understood, in the study area, by studying extreme PM₁₀ events mutually with large-scale atmospheric circulation and this is the aim of the next chapter.

PM₁₀ Extreme Events and Large-scale Atmospheric Circulation

After exploring the correlation between PM₁₀ averages and climate indexes, there was a need for further assessment of how could large-scale atmospheric circulation affect the emergence of extreme PM₁₀ events. Accordingly, and in order to reduce the probability of having the episodes triggered by local pollution in the cities of Casablanca and Marrakech, seasonal PM₁₀ episodes common to both cities were identified. For the purpose of this work, a common PM₁₀ episode is defined as an extreme PM₁₀ event recorded on the same day in the two cities, offset days of episodes' appearances were not considered. We have identified more than 70 recorded PM₁₀ episodes in each city between 2013 and 2016: 16 were common to both cities, 5 in autumn and spring each and 3 in winter and summer each. The maps of SLP fields from ECMWF were reconstructed and analyzed for all the common episodes, they correspond to the weather types. This step helped to identify atmospheric flows behind detected common extremes.

Fig. 6 shows seasonal weather types related to samples of common extreme PM₁₀ events. For all the reconstructed

Fig. 5. Correlation between annual climate indexes (NAO and MO) and PM₁₀ averages.

Table 1. Spearman coefficient of correlation between annual and seasonal PM₁₀ averages and Climate Indexes (NAO, MO, SaOI).

Site	Annual			Autumn			Winter			Spring			Summer		
	NAO	MO	SaOI	NAO	MO	SaOI	NAO	MO	SaOI	NAO	MO	SaOI	NAO	MO	SaOI
Casablanca	0.21	0.32	-0.17	0.12	0.42	0.13	0.00	0.56	-0.42	0.15	0.31	-0.13	0.07	0.35	0.01
Marrakech	0.09	0.46	-0.26	0.16	0.46	0.03	0.06	0.53	-0.52	0.10	0.40	-0.18	0.12	0.29	-0.07
NAO	–	–	0.19	–	–	0.31	–	–	0.24	–	–	0.23	–	–	0.26
MO	–	–	-0.04	–	–	0.04	–	–	-0.24	–	–	0.10	–	–	0.08

Bold characters: coefficient is statistically significant (significance level = 0.05).

weather types, Morocco is under continental northeasterly to southwesterly flows. For each season, one weather type coincides with the appearance of all the common seasonal PM₁₀ episodes. In autumn (Fig. 6(a)), Morocco is under the combined influence of the large high-pressure area, merging the high that extends over the whole European continent and the Azores High that covers the Atlantic region in the west of the country, and the Saharan trough strengthening toward the country. Thus, the area is receiving a south to southeasterly flow that favors the transport of particulate matter from the desert and a north to northeasterly flow that favors its stagnation over the studied area mainly the coastal city of Casablanca. The anticyclonic stagnation conditions in the north and the west of the country can clarify the significant correlations found between both NAO and MO indexes and PM₁₀ averages in autumn. In winter (Fig. 6(b)), the high-pressure area in the north of Morocco strengthens and invades the country, it extends over North Africa and causes the recession of the Saharan trough. The flow is northeasterly to easterly, continental from over the desert in the east of Morocco. This is a blocking synoptic pattern that worsens local pollution conditions and may increase sensitivity in

patients suffering from respiratory diseases. The influence of the anticyclonic conditions from the north and the weakening of the anticyclonic area in the west may explain the significance and the importance of winter PM₁₀/MO correlations, whereas no correlations were found between PM₁₀ and NAO index. In all autumn and winter episodes, Casablanca has recorded the most important PM₁₀ concentrations. This is in accordance with our previous findings and can partly explain why autumn and winter PM₁₀ averages are more important in Casablanca than in Marrakech. In spring (Fig. 6(c)), the correlation PM₁₀/MO keeps to be statistically significant. Blocking conditions are relieved and the Saharan trough invades the country from the south on account of the northern high which weakens and retreats. The impact of the Saharan flow reaches the European continent as well. With this synoptic pattern, the flow in the study area is southerly continental transporting particulate matter from the desert. The inland city of Marrakech recorded higher PM₁₀ concentrations in most extreme cases, yet Casablanca has recorded higher PM₁₀ averages in spring. In summer (Fig. 6(d)), the Saharan trough extends toward the north of the country, including the

Fig. 6. Seasonal sea-level pressure (MSLP) related to a sample of recorded extreme PM_{10} events: MSLP on (a) 28 September 2016 (autumn), (b) 18 December 2015 (winter), (c) 17 April 2013 (spring), (d) 19 July 2016 (summer).

northern coasts and reaches the European continent where the observed high may create blocking conditions. The Saharan flow that crosses the study area favors southerly flows and fosters high temporary PM_{10} concentrations, yet no stagnation conditions are noticed over the country. In all observed summer situations, Marrakech has recorded higher PM_{10} concentrations than Casablanca in accordance with the fact that Marrakech records higher average PM_{10} concentrations in summer. Even though they weaken, anticyclonic conditions in the north of the study area keep having an impact on the flow invading it; this explains the weak and statistically significant PM_{10}/MO correlation during summer.

The performed analysis has shown that average PM_{10} concentrations and extreme events observed over the studied area are the repercussion of the interactions between anticyclonic areas in the north and the west of Morocco and the cyclonic conditions in the south of the kingdom. The nature of this high-low interaction controls the level of particle pollution in the south inland of the country, represented by the city of Marrakech, and the north coasts, denoted by the city of Casablanca. This finding emerged the need of building an index, similar to NAO and MO indexes, that may describe the southern anticyclonic-cyclonic oscillation and express the southern flow impact. This index will be called the *Saharan Oscillation Index*.

The Saharan Oscillation Index: Formulation and Correlations

For the purpose of this work, the Saharan oscillation (SaO) is suggested to be related to the dipole between the Azores High and the Saharan trough. The SaOI is defined as the difference between the normalized pressure of the Azores ($37.79^{\circ}N, -25.5^{\circ}E$) from Portugal, as the supposed center of the Azores High, and the normalized pressure in Niamey ($13.51^{\circ}N, 2.10^{\circ}E$) from Niger, as the theoretical center of the Saharan depression area (Eq. (1)). The calculations were performed on a daily basis in order to prepare SaOI time series between 2013 and 2016.

$$SaOI_d = Pn_d(Azores) - Pn_d(Niamey) \quad (1)$$

$SaOI_d$: daily Saharan Oscillation Index;
 Pn_d : daily normalized pressure between 2013 and 2016.

The evolution of the SaOI data between 2013 and 2016 is shown in Fig. 7. The index ranges between -0.8 and 0.8 and evolves according to a cyclical pattern. Positive values are preponderant and negative values do not exceed 15% each year. Many oscillations occur all over the studied period. No clear relationship was found between the sign of the SaOI and extreme PM_{10} events. Spearman coefficient of correlation was calculated between annual and seasonal SaOI and PM_{10}

Fig. 7. Evolution of the daily SaOI data between 2013 and 2016.

averages for Casablanca and Marrakech, and between SaOI, NAO and MO indexes. The significance level is 0.05. Results are shown in Table 1. Annual PM_{10} averages and SaOI datasets are negatively correlated. These correlations are statistically significant and coefficients are of the same order in both cities (Table 1). This informs about seasonal PM_{10} /SaOI relationship. In autumn, PM_{10} /SaOI coefficient of correlation is weak, positive and statistically significant in Casablanca. It is negative and statistically significant in both cities in spring. In winter, PM_{10} /SaOI correlations are negative, moderate and statistically significant for both cities. SaOI keeps to be positively correlated with NAO in all seasons, while it is negatively correlated with the MO in winter. Coefficients of correlation are statistically significant and are of the same order in both cities.

The results show that SaO and MO contribute mutually to particle pollution in Morocco, mainly in winter. The transport of particles from the southern desert is ensured by the Saharan flow while the Mediterranean flow controls their concentrations. The role of NAO in this operation remains minor. The level of local pollution by PM_{10} is accentuated by large-scale atmospheric circulation that either transport fine particles from the southern desert or generate stagnation conditions and then cause PM_{10} concentrations to increase in both cases. It may also be impacted by humidity. This may explain the difference between recorded extreme PM_{10} concentrations in the coastal city of Casablanca and the city of Marrakech which is inland. Our findings are somehow similar to those of Pateraki *et al.* (2012) that showed that high PM_{10} concentrations, in the Mediterranean area, are closely related to the southwesterly regime, suggesting long-range transport from the polluted south sector.

CONCLUSION

Although previous research has examined PM_{10} pollution in Casablanca and Marrakech, two highly populated Moroccan cities, our study is the first attempt to assess its potential relationship with large-scale atmospheric circulation. We

determined trends in the PM_{10} by analyzing daily measured concentrations for the period 2013–2016. Identifying extreme events involving this pollutant and following their evolution, we then investigated the contribution of large-scale atmospheric circulation to the PM_{10} by correlating the time series of the average concentrations with climate indexes (NAO and MO) and establishing weather patterns that coincided with the episodes.

Despite not revealing obvious tendencies for the average concentrations or the extreme events, our study demonstrates that the PM_{10} level depends both on the specific city—hence, local sources—and on large-scale atmospheric circulation according to the season—thus, meteorological parameters such as the temperature, humidity and wind. When more data becomes available, the contribution from each source may be estimated. Additionally, our results show a relationship between the NAO and MO climate indexes and the average PM_{10} concentrations, proving that the MO plays a major role in particulate pollution in Morocco, and help to define the Saharan oscillation (SaO) as the interaction between the Azores High and the Saharan depression. With the continual transport of particles from the south, the SaO may be a factor that enhances our understanding of this pollution in Morocco; thus, we formulated the Saharan Oscillation Index (SaOI) at the surface level, a new index for this phenomenon, and calculated the related correlations. Future research will focus on computing this index, obtaining time series for different atmospheric levels (850 hPa, 700 hPa, 500 hPa and 200 hPa) and evaluating the contribution of the SaO to PM_{10} in Morocco all year round.

Our work takes the first step in exploring the hypothesis that particular weather patterns increase the vulnerability of individuals with respiratory disease. Additional studies may aid the establishment of an alert system and provide recommendations for coping with PM_{10} episodes.

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