The contribution of large-scale atmospheric patterns to pollution with PM$_{10}$: the new Saharan Oscillation Index

Kenza Khomsi$^{1,2,*}$, Houda Najmi$^1$, Youssef Chelhaoui$^1$, Zineb Souhaili$^2$

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

$^2$Laboratory of Drugs Science, Biomedical and Biotecnological Research. Faculty of Medicine and Pharmacy. Hassan II University; Ain Chock, Casablanca; P.B. 5696, Morocco

Abstract

PM$_{10}$ has natural and anthropogenic sources, it is an urban air pollutant from desertic areas or emitted by industry and traffic activities, it reduces visibility and threatens human wellbeing mainly in big cities.

Casablanca concentrates many industrial units and a large vehicle fleet. The rate of urbanization in the metropolis and the population density are the highest in Morocco. Marrakech is one of the most populated cities in the country where the motorization rate has increased during recent years.

The present work is based on PM$_{10}$ daily measurements between 2013 and 2016. The main objective is to assess the concentrations of PM$_{10}$ in Casablanca and Marrakech and study their relationship with the atmospheric circulation. First, we assessed PM$_{10}$ correlations with climate indexes (the North Atlantic Oscillation (NAO) and the Mediterranean Oscillation (MO)), then we characterized the contribution of large-scale atmospheric patterns related to PM$_{10}$ extreme events. The novelty of this research is the creation of a new climate index to characterize the oscillation, in the country’s southern desert, between the Saharan depression and the Azores high. The time series of the new Saharan Oscillation Index (SaOI) were calculated.

This study has demonstrated the relationship between MO and PM$_{10}$ averages and has shown that particulate pollution in the study area is partly induced by continental northeasterly to southwesterly flow. This flow is triggered by the Saharan trough and managed by the high-pressure area in the north. The assessed correlations related to the SaOI confirm the relationship between this index, PM$_{10}$ averages, and MO and NAO indexes mainly in winter.

Keywords: Particulate Matter (PM$_{10}$); Correlation; Saharan Depression; Climate Index; Saharan Oscillation Index (SaOI); Air Quality

1. Introduction

* E-mail address: k.khomsi@gmail.com
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 pollutant (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, wellbeing 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). PM$_{10}$ 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 of visibility, smoke, haze, and smog (Agustine et al., 2018).

Weather conditions and meteorological factors play a crucial role in air pollution, mainly by PM$_{10}$, 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 PM$_{10}$ 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 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, PM$_{10}$ 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 PM$_{10}$. 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, 2017a; Inchaouh, 2017b; Inchaouh et al., 2018).

The goal of this study is to evaluate the concentrations of PM$_{10}$ 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 (Khomsi 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 PM$_{10}$ 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 PM$_{10}$ 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 PM$_{10}$ 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 PM$_{10}$ averages and extremes, we show PM$_{10}$ seasonal correlations with NAO and MO indexes and we identify and analyze synoptic patterns behind the occurrence of PM$_{10}$ extremes. Finally, we suggest the elaboration of a new climate index; the Saharan Oscillation Index (SaOI) and assess its relationship with PM$_{10}$, NAO and MO indexes.

2. Materials and Methods

2.1. 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 (Khomsi, 2013; Filahi et al., 2015; Khomsi et al., 2016; Filahi et al., 2017; Kamal et al., 2018; Khomsi et al., 2018) and accordingly extreme related pollution episodes.

Casablanca and Marrakech are, respectively, the first and the fourth populous cities in Morocco with more than 3,000,000 and 900,000 residents, respectively, as reported by the World Population Review webpage (2020). 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.

2.2.  PM$_{10}$ data

Daily mean data of PM$_{10}$ concentrations (in μg/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 J. et al., 2003). For the
purpose of this work, PM$_{10}$ 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.

2.3.  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 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 PM$_{10}$ averages between 2013 and 2016.

2.4. Sea Level Pressure (SLP) data

Daily data were used in order to retrace SLP patterns related to the identified PM$_{10}$ 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 ERA 5 reanalysis. ERA5 is the latest climate reanalysis data generated by the European Center 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) on unvarying latitude-longitude grids at 0.25° × 0.25° resolution (https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset).

2.5. Methods

To identify extreme events in PM$_{10}$, the overall and seasonal 95$^{th}$ percentiles computed across the whole-time period were used as thresholds. The 95$^{th}$ 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://ccma.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 95$^{\text{th}}$ percentile.

The magnitudes of trends in time series were analyzed using the non-parametric approach proposed by Theil and Sen (Sen, 1968; Theil, 1992) 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 (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).

3. Results and discussion

3.1. 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, 2017a). Concerning extreme
events, observed frequencies are of the same order in both cities in winter and summer. Extreme
events 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
µg/m$^3$(WHO, 2006). This finding is in agreement with the previous studies of (Croitoru and
Sarraf, 2017; Inchaouh, 2017a; Inchaouh et al., 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 (Khomsi 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.

3.2. 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 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 PM$_{10}$ concentrations. Anticyclonic settings are generally related to stagnation conditions that disadvantage dispersion and foster PM$_{10}$ concentrations. These findings are confirmed by the previous results of (Pateraki et al., 2012; Hsu and Cheng, 2019; Toro et al., 2019), that have proved the interactions between anticyclonic conditions and PM$_{10}$ high concentrations in the Mediterranean area, Taiwan and Chile, respectively. These interactions will be better understood, in the study area, by studying extreme PM$_{10}$ events mutually with large scale atmospheric circulation and this is the aim of the next chapter.

3.3. PM$_{10}$ extreme events and large-scale atmospheric circulation

After exploring the correlation between PM$_{10}$ averages and climate indexes, there was a need for further assessment of how could large scale atmospheric circulation affect the emergence of
extreme PM$_{10}$ 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 common PM$_{10}$ episodes to both cities were identified. For the purpose of this work, a common PM$_{10}$ episode is defined as an extreme PM$_{10}$ event recorded on the same day in the two cities, offset days of episodes appearance were not considered. We have identified more than 70 recorded PM$_{10}$ 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 PM$_{10}$ events. For all the reconstructed weather types, Morocco is under continental east-northerly to south-westerly flows. For each season, one weather type coincides with the appearance of all the common seasonal PM$_{10}$ 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 PM$_{10}$ 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 PM$_{10}$/MO correlations, whereas no correlations were found between PM$_{10}$
and NAO index. In all autumn and winter episodes, Casablanca has recorded the most important
PM$_{10}$ concentrations. This is in accordance with our previous findings and can partly explain why
autumn and winter PM$_{10}$ averages are more important in Casablanca than in Marrakech. In spring
(Fig. 6 (c)), the correlation PM$_{10}$/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 witch 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 PM$_{10}$
concentrations in most extreme cases, yet Casablanca has recorded higher PM$_{10}$ averages in
spring. In summer (Fig. 6 (d)), the Saharan trough extends toward the north of the country, including the 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 evading the study area; 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 (SaOI).
3.4. The Saharan Oscillation Index (SaOI): formulation and correlations

For the purpose of this work, a 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°N, -25.5°E) from Portugal, as the supposed center of the Azores High, and the normalized pressure in Niamey (13.54°N, 2.40°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.

\[
SaOI_d = Pn_d(Azores) - Pn_d(Niamey) \tag{Equation 1}
\]

| Sample Code | Description |
|-------------|-------------|
| 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 range 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$_{10}$ averages for Casablanca and Marrakech, and between SaOI, NAO and MO indexes. The significance level is 0.05. Results are shown 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 in the 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.
4. Conclusion

Although previous studies have examined particle pollution by PM$_{10}$ in Casablanca and Marrakech, this study was the first attempt to assess the possible relationship between this type of pollution and large-scale atmospheric circulation in the two highly populated cities in Morocco. We have assessed trends in average PM$_{10}$ by analyzing daily measurements of PM$_{10}$ concentrations for the period between 2013 and 2016. We identified PM$_{10}$ extreme events and assessed their evolution and then we discovered how large-scale atmospheric circulation contributes to pollution by PM$_{10}$; we first studied the correlation of average PM$_{10}$ time series and climate indexes (NAO & MO) and then identified weather patterns that match the occurrence of particle pollution events.

Our study did not reveal any accentuated tendencies for PM$_{10}$ averages and extreme events; however, it showed that the concentrations of this pollutant depend on the city and thus on the local sources of particles. They also depend on the large-scale atmospheric circulation according to the seasons and thus on meteorological parameters like the temperature, the humidity and the wind. When more data is available, contributions from each source type may be identified. Moreover, this work has shown a relationship between the NAO and the MO climate indexes and PM$_{10}$ averages, it has proved that the MO plays a major role in particle pollution in Morocco. It has also helped to define the Saharan Oscillation (SaO) as the interaction between the Azores
High and the Saharan Depression, the SaO may be a new factor that helps understand this type of pollution in Morocco, considering the continuous transport of particles from the south. A new SaO related index: the Saharan Oscillation Index (SaOI), was formulated and computed. The SaOI was calculated and related correlations were assessed on the surface level. A future research will focus in computing this index, preparing time series at different atmospheric levels (850 hPa, 700 hPa, 500 hPa and 200 hPa) and assessing the contribution of this index to pollution by PM$_{10}$ in Morocco during all seasons.

The present study may be the first step with the hypothesis that particular weather patterns accentuate health vulnerability of patients with respiratory diseases. Further studies could possibly help establishing an alert system and be used to make recommendations during higher levels of PM$_{10}$ and would help to develop reasonable policies for coping with particle pollution episodes.

Acknowledgements:

The authors thank Dr Sihem Aouabdi who edited the English language of the paper on behalf of the Science Edit For The Developing World.

References

Morocco Population, http://worldpopulationreview.com/countries/morocco/, Last Access: 16/01/2020.

(IHME), I.f.H.M.a.E. (2018). Findings from the Global Burden of Disease Study 2017, Seattle, WA.
Agustine, I., Yulianawati, H., Gunawan, D. and Suswantoro, E. (2018). Potential Impact of Particulate Matter Less Than 10 Micron (PM$_{10}$) to Ambient Air Quality of Jakarta and Palembang. *IOP Conference Series: Earth and Environmental Science* 106.

Almeida, C.T., Oliveira-Júnior, J.F., Delgado, R.C., Cubo, P. and Ramos, M.C. (2017). Spatiotemporal Rainfall and Temperature Trends Throughout the Brazilian Legal Amazon, 1973-2013. *International Journal of Climatology* 37: 2013-2026.

Alves, C., Calvo, A.I., Marques, L., Castro, A., Nunes, T., Coz, E. and Fraile, R. (2014). Particulate Matter in the Indoor and Outdoor Air of a Gymnasium and a Fronton. *Environ Sci Pollut Res Int* 21: 12390-12402.

Ambaum, M.H.P., Hoskins, B.J. and Stephenson, D.B. (2001). Arctic Oscillation or North Atlantic Oscillation? *Journal of Climate* 14: 3495-3507.

An, Z., Jin, Y., Li, J., Li, W. and Wu, W. (2018). Impact of Particulate Air Pollution on Cardiovascular Health. *Curr Allergy Asthma Rep* 18: 15.

Analitis, A., De' Donato, F., Scotto, M., Lanki, T., Basagana, X., Ballester, F., Estrada, C., Paldy, A., Pascal, M., Gasparri, A., Michelozzi, P. and Katsouyanni, K. (2018). Synergistic Effects of Ambient Temperature and Air Pollution on Health in Europe: Results from the Phase Project. *Int J Environ Res Public Health* 15.

Baltacı, H., Akkoyunlu, B.O. and Tayanç, M. (2017). Relationships between Teleconnection Patterns and Turkish Climatic Extremes. *Theoretical and Applied Climatology* 134: 1365-1386.

Byakatonda, J., Parida, B.P., Kenabatho, P.K. and Moalafhi, D.B. (2018). Analysis of Rainfall and Temperature Time Series to Detect Long-Term Climatic Trends and Variability over Semi-Arid Botswana. *Journal of Earth System Science* 127.

Cheng, B. and Wang-Li, L. (2019). Spatial and Temporal Variations of PM$_{2.5}$ in North Carolina. *Aerosol and Air Quality Research* 19: 698-710.

Conte, M., Giuffrida, A. and Tedesco, S. (1989). Mediterranean Oscillation: Impact on Precipitation and Hydrology in Italy. In *Conf. Clim. Water*.

Croitoru, L. and Sarraf, M. (2015). Estimating the Health Cost of Air Pollution: The Case of Morocco. *Journal of Environmental Protection* 08: 1087-1099.

Czernecki, B., Polonovich, M., Kolendowicz, L., Marosz, M., Kendzierski, S. and Pilguj, N. (2016). Influence of the Atmospheric Conditions on PM$_{10}$ Concentrations in Poznań, Poland. *Journal of Atmospheric Chemistry* 74: 115-139.

Dougdour, A. (1995). Régionalisation of the Winter Precipitation in the Mediterranean Basin : A Mediterranean Oscillation ?, In *Atmospheric Physics and Dynamics in the Analysis and Prognosis of Precipitation Fields*, S. Palmieri, La Sapienza, Rome.

Drumond, A., Gimeno, L., Nieto, R., Trigo, R.M. and Vicente-Serrano, S.M. (2017). Drought Episodes in the Climatological Sinks of the Mediterranean Moisture Source: The Role of Moisture Transport. *Global and Planetary Change* 151: 4-14.

Egberts, V., van Schaik, G., Brunekreef, B. and Hoek, G. (2019). Short-Term Effects of Air Pollution and Temperature on Cattle Mortality in the Netherlands. *Prev Vet Med* 168: 1-8.
Filahi, S., Tanarhte, M., Mouhir, L., El Morhit, M. and Tramblay, Y. (2015). Trends in Indices of Daily Temperature and Precipitations Extremes in Morocco. *Theoretical and Applied Climatology* 124: 959-972.

Filahi, S., Tramblay, Y., Mouhir, L. and Diaconescu, E.P. (2017). Projected Changes in Temperature and Precipitation Indices in Morocco from High-Resolution Regional Climate Models. *International Journal of Climatology* 37: 4846-4863.

Gugamsetty, B., Wei, H., Liu, C.-N., Awasthi, A., Hsu, S.-C., Tsai, C.-J., Roam, G.-D., Wu, Y.-C. and Chen, C.-F. (2012). Source Characterization and Apportionment of PM$_{10}$, PM$_{2.5}$ and PM$_{0.1}$ by Using Positive Matrix Factorization. *Aerosol and Air Quality Research* 12: 476-491.

Guo, J. (2018). The Costs of Climate Change. *IOP Conference Series: Earth and Environmental Science* 120.

Hamed, K.H. and Ramachandra Rao, A. (1998). A Modified Mann-Kendall Trend Test for Autocorrelated Data. *Journal of Hydrology* 204: 182–196.

Hänsel, S., Schucknecht, A. and Matschullat, J. (2015). The Modified Rainfall Anomaly Index (Mrai)—Is This an Alternative to the Standardised Precipitation Index (SPI) in Evaluating Future Extreme Precipitation Characteristics? *Theoretical and Applied Climatology* 123: 827-844.

Hopke, P.K., Hashemi Nazari, S.S., Hadei, M., Yarahmadi, M., Kermann, M., Yarahmadi, E. and Shahsavani, A. (2018). Spatial and Temporal Trends of Short-Term Health Impacts of PM$_{2.5}$ in Iranian Cities; a Modelling Approach (2013-2016). *Aerosol and Air Quality Research* 18: 497-504.

Hsu, C.-H. and Cheng, F.-Y. (2019). Synoptic Weather Patterns and Associated Air Pollution in Taiwan. *Aerosol and Air Quality Research* 19: 1139–1151.

Inchaouh, M. (2017a). State of Ambient Air Quality in Marrakech City (Morocco) over the Period 2009 – 2012. *International Journal of GEOMATE*.

Inchaouh, M., Khomsi, K. and Tahiri, P.M. (2018). Ambient Air Quality Assessment in the Grand Casablanca Area (Morocco): Impact of Road Traffic Emissions for the 2013-2016 Period. *Energy and Earth Science* 1.

Inchaouh, M., Tahiri, M. (2017b). Air Pollution Due to Road Transportation in Morocco: Evolution and Impacts. *Journal of Multidisciplinary Engineering Science and Technology* 4: 7547-7552.

Kahsay, K.D., Pingale, S.M. and Hatiye, S.D. (2018). Impact of Climate Change on Groundwater Recharge and Base Flow in the Sub-Catchment of Tekeze Basin, Ethiopia. *Groundwater for Sustainable Development* 6: 121-133.

Kalisa, E., Fadlallah, S., Amani, M., Nahayo, L. and Habiyaremye, G. (2018). Temperature and Air Pollution Relationship During Heatwaves in Birmingham, Uk. *Sustainable Cities and Society* 43: 111-120.

Kamal, A.O., Ismail, K., Abdelkrim, A., Atika, K., Driss, E., Ezzahra, E.F., Zakaria, A., Fatima, N. and Nadia, N. (2018). Climate Change Trend Observations in Morocco: Case Study of Beni Mellal-Khenitra and Dar&#226;a-Tafilalt Regions. *Journal of Geoscience and Environment Protection* 06: 34-50.

Kamruzzaman, M., Rahman, A.T.M.S., Ahmed, M.S., Kabir, M.E., Mazumder, Q.H., Rahman, M.S. and Jahan, C.S. (2016). Spatio-Temporal Analysis of Climatic Variables in the Western Part of Bangladesh. *Environment, Development and Sustainability* 20: 89-108.
Khaefi, M., Geravandi, S., Hassani, G., Yari, A.R., Soltani, F., Dobaradaran, S., Moogahi, S., Mohammadi, M.J., Mahboubi, M., Alavi, N., Farhadi, M. and Khaniabadi, Y.O. (2017). Association of Particulate Matter Impact on Prevalence of Chronic Obstructive Pulmonary Disease in Ahvaz, Southwest Iran During 2009–2013. *Aerosol and Air Quality Research* 17: 230-237.

Khomsi, K., Mahe, G., Tramblay, Y., Sinan, M. and Snoussi, M. (2016). Regional Impacts of Global Change: Seasonal Trends in Extreme Rainfall, Run-Off and Temperature in Two Contrasting Regions of Morocco. *Natural Hazards and Earth System Sciences* 16: 1079-1090.

Khomsi, K., Mahe, G., Sinan, M., Snoussi, M. (2013). Hydroclimatic Variability in Two Moroccan Basins: Comparative Analysis of Temperature, Rainfall and Runoff Regimes, In *IAHS-AISH Proceedings and Reports*.

Khomsi, K., Najmi, H. and Souhaili, Z. (2018). Co-Occurrence of Extreme Ozone and Heat Waves in Two Cities from Morocco. *Satellite Oceanography and Meteorology* 3.

Kliengchuay, W., Cooper Meeyai, A., Worakhunpiset, S. and Tantrakarnapa, K. (2018). Relationships between Meteorological Parameters and Particulate Matter in Mae Hong Son Province, Thailand. *Int J Environ Res Public Health* 15.

Kusumaningtyas, S.D.A., Aldrian, E., Wati, T., Atmoko, D. and Sunaryo, S. (2018). The Recent State of Ambient Air Quality in Jakarta. *Aerosol and Air Quality Research* 18: 2343-2354.

Li, H.Z., Gu, P., Ye, Q., Zimmerman, N., Robinson, E.S., Subramanian, R., Apte, J.S., Robinson, A.L. and Presto, A.A. (2019). Spatially Dense Air Pollutant Sampling: Implications of Spatial Variability on the Representativeness of Stationary Air Pollutant Monitors. *Atmospheric Environment: X* 2.

Mendez-Lázaro, P., Muller-Karger, F.E., Otis, D., McCarthy, M.J. and Pena-Orellana, M. (2014). Assessing Climate Variability Effects on Dengue Incidence in San Juan, Puerto Rico. *Int J Environ Res Public Health* 11: 9409-9428.

Molina, C., Toro A, R., Morales S, R.G.E., Manzano, C. and Leiva-Guzmán, M.A. (2017). Particulate Matter in Urban Areas of South-Central Chile Exceeds Air Quality Standards. *Air Quality, Atmosphere & Health* 10: 653-667.

Pateraki, S., Asimakopoulou, D.N., Flocas, H.A., Maggos, T. and Vasilakos, C. (2012). The Role of Meteorology on Different Sized Aerosol Fractions (PM_{10}, PM_{2.5}, PM_{2.5-10}). *Sci Total Environ* 419: 124-135.

Şahin, S., Ivanov, M. and Türkş, M. (2018). Control of Dry and Wet Januaries and Winters in the Mediterranean Basin by Large-Scale Atmospheric Moisture Flux and Its Convergence. *Journal of Hydrology* 566: 616-626.
Sen, P.K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association* 63: 1379-1389.

Sfîcă, L., Iordache, I., Ichim, P., Leahu, A., Cazacu, M.-M., Gurlui, S. and Trif, C.-R. (2018). The Influence of Weather Conditions and Local Climate on Particulate Matter (PM_{10}) Concentration in Metropolitan Area of Iasi, Romania. *Present Environment and Sustainable Development* 12: 47-69.

Tecer, L.H., Suren, P., Alagha, O., Karaca, F. and Tuncel, G. (2008). Effect of Meteorological Parameters on Fine and Coarse Particulate Matter Mass Concentration in a Coal-Mining Area in Zonguldak, Turkey. *J Air Waste Manag Assc* 58: 543-552.

Theil, H. (1992). A Rank-Invariant Method of Linear and Polynomial Regression Analysis, In *Henri Theil's Contributions to Economics and Econometrics*, pp. 345–381.

Toro, A.R., Kvakic, M., Klaic, Z.B., Koracin, D., Morales, S.R. and Leiva, G.M. (2019). Exploring Atmospheric Stagnation During a Severe Particulate Matter Air Pollution Episode over Complex Terrain in Santiago, Chile. *Environ Pollut* 244: 705-714.

von Schneidemesser, E., Monks, P.S., Allan, J.D., Bruhwiler, L., Forster, P., Fowler, D., Lauer, A., Morgan, W.T., Paasonen, P., Righi, M., Sindelarova, K. and Sutton, M.A. (2015). Chemistry and the Linkages between Air Quality and Climate Change. *Chem Rev* 115: 3856-3897.

WHO (2014). 7 Million Premature Deaths Annually Linked to Air Pollution, WHO (Ed.), Geneva.

WHO (2006). *Air Quality Guidelines Global Update 2005: Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide*, Copenhagen p. 10.
Table 1: Spearman coefficient of correlation between annual and seasonal PM\textsubscript{10} averages and Climate Indexes (NAO, MO, SaOI)

| Site       | Annual | Autumn | Winter | Spring | Summer |
|------------|--------|--------|--------|--------|--------|
|            | NA     | M      | SaO    | NA     | M      | SaO    | NA     | M      | SaO    | NA     | M      | SaO    | NA     | M      | SaO    | NA     | M      | SaO    |
| Casablanca | 0.21   | 0.3    | -      | 0.12   | 0.4    | 0.13   | 0.00   | 0.5    | -      | 0.15   | 0.3    | -      | 0.07   | 0.3    | 0.01   |
| Marrakech  | 0.09   | 0.4    | -      | 0.16   | 0.4    | 0.03   | 0.06   | 0.5    | -      | 0.4    | -      | 0.13   | 0.2    | -      | 0.07   |
| NAO        | -      | -      | 0.19   | -      | -      | 0.31   | -      | -      | 0.24   | -      | 0.23   | -      | -      | 0.26   |
| MO         | -      | -      | -      | -      | 0.04   | -      | -      | -      | -      | -      | 0.10   | -      | -      | 0.08   |

Bold Character: Coefficient is statistically significant, Significance level = 0.05
Figure Captions

**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

**Fig. 2.** Evolution of annual PM$_{10}$ averages and extreme events.

**Fig. 3.** Evolution of seasonal PM$_{10}$ averages and extreme events. a) autumn, b) winter, c) spring, d) summer.

**Fig. 4.** Overall and seasonal PM$_{10}$ thresholds for PM$_{10}$ extreme events

**Fig. 5.** Correlation between annual climate indexes (NAO & MO) and PM$_{10}$ averages

**Fig. 6.** Seasonal Sea Level Pressure (MSLP) related to a sample of recorded extreme PM$_{10}$ events.

a) MSLP on the 28/09/2016 (autumn), b) MSLP on the 18/12/2015 (winter), c) MSLP on the 17/04/2013 (spring), d) MSLP on the 19/07/2016 (summer).

**Fig. 7.** Evolution of the daily SaOI data, between 2013 and 2016
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 6.