Concurrent heatwaves and extreme Ozone (O3) episodes: combined atmospheric patterns and impact on human health

Kenza Khomsi[1,1], Youssef Chelhaoui[2,2], Soukaina Alilou[3,3], Rania Souri[3,3], Houda Najmi[2,2], and Zineb Souhaili[4,4]

[1]General Directorate of Meteorolgy
[2]General Directorate of Meteorology
[3]Hassania School of Public Works
[4]Laboratory of Drugs Science, Biomedical and Biotechnological Research. Faculty of Medicine and Pharmacy

November 30, 2022

Abstract

More recurrent heatwaves and extreme ozone episodes are likely to occur during the next decades and a key question is about the concurrence of those hazards, the atmospheric patterns behind their appearance and their joint effect on human health. In this work, we use surface maximum temperature and O3 observations during extended summers in two cities from Morocco: Casablanca and Marrakech, between 2010 and 2019. We assess the connection between these data and climate indexes (North Atlantic Oscillation (NAO), Mediterranean Oscillation (MO) and Saharan Oscillation (SaOI)). We then identify concurrent heatwaves and ozone episodes, the weather type behind this concurrence and the combined health risks. Our findings show that the concurrence of heatwaves and O3 episodes depends both on the specific city and the large-scale atmospheric circulation. The likely identified synoptic pattern is when the country is under the combined influence of an anticyclonic area in the north and the Saharan trough extending the depression centered in the south. This pattern generates a warm flow and may foster photochemical pollution. Our study is the first step towards the establishment of an alert system. It will help to provide recommendations for coping with concurrent heatwaves and air pollution episodes.

Article

Concurrent heatwaves and extreme Ozone (O3) episodes: combined atmospheric patterns and impact on human health

Kenza Khomsi [1,2,*], Youssef Chelhaoui [1], Soukaina Alilou[3], Rania Souri[3], Houda Najmi [1] and Zineb Souhaili [2]

[1] General Directorate of Meteorology; Casablanca, Morocco
[2] Laboratory of Drugs Science, Biomedical and Biotechnological Research. Faculty of Medicine and Pharmacy; Casablanca, Morocco

* Correspondence: k.khomsi@gmail.com

Received: date; Accepted: date; Published: date

Abstract: More recurrent heatwaves and extreme ozone episodes are likely to occur during the next decades and a key question is about the concurrence of those hazards, the atmospheric patterns behind their appearance and their joint effect on human health. In this work, we use surface maximum temperature and O_3 observations during extended summers in two cities from Morocco: Casablanca and Marrakech, between 2010 and 2019. We assess the connection between these data and climate indexes (North Atlantic Oscillation (NAO), Mediterranean Oscillation (MO) and Saharan Oscillation (SaOI)). We then identify concurrent heatwaves and ozone episodes, the weather type behind this concurrence and the combined health risks. Our findings show that the concurrence of heatwaves and O_3 episodes depends both on the specific city and the large-scale atmospheric circulation. The likely identified synoptic pattern is when the country is under the combined influence of an anticyclonic area in the north and the Saharan trough extending the depression centered in the south. This pattern generates a warm flow and may foster photochemical pollution. Our study is the first step towards the establishment of an alert system. It will help to provide recommendations for coping with concurrent heatwaves and air pollution episodes.

Keywords: Heatwave, Ozone episode, Morocco, NAO, MO, SaO, Human health

---

1. Introduction

Industrial and traffic activities emit various pollutants that are harmful to human health. Ozone (O_3) is among these air pollutants. Ozone is formed by a complex photochemical interaction triggered by sunlight and the presence of nitrogen oxides (NO_X), or volatile organic compounds (VOCs). The latter can act as a sink or source of ozone depending on their availability [1,2]. The total chemical balance is:

$$+h \rightarrow +$$

$$+_2 \rightarrow _3$$

$$2+2 \rightarrow +3$$

According to [3], these reactions may be potentiated by higher air temperatures exceeding 20°C; the highest ozone mixing ratios are observed under the warmest conditions. Consequently, the ambient O_3 concentration is governed both by the emissions of its precursors, VOCs and NOx, and by the meteorological state. Temperature is the main meteorological factor to be directly involved in resulting in ozone extreme events [1,2].

Within this framework, several studies have been carried out at national and international levels. In the Pearl River Delta region from China for example, [1] used measured surface ozone concentration and meteorological parameters to study the impact of local meteorological events on O_3 spatio-temporal concentration during the extended summer (April-October), between 2006 and 2017. Authors show that ozone formation is triggered when temperatures exceed 33°C and that extreme ozone events are largely initiated by hot events. Heatwaves increase the ozone exceedance rate by 2.5 times. Another study was carried out over Europe to assess the relationship between local and synoptic meteorological conditions and surface ozone concentration in spring and summer, over the period 1998-2012 [4]. It has shown that climate change is expected to affect regional meteorological conditions, such as warmer temperatures or stagnant conditions, as well as increase heatwaves that affect ozone levels. The study has also identified regions, in Europe, that may be particularly vulnerable to increased ozone episodes. In Sydney, Australia, [2] showed that hot events occurrence may worsen air quality levels in the city.

In Morocco, [5] studied the concurrence of extreme ozone and hot events in two urban cities during the extended summer (April-September), between 2009 and 2016. The study showed that 33% of hot events were accompanied by extreme ozone episodes in the coastal city of Casablanca, as compared to 70% in the inland city of Marrakech. This has questioned the role that humidity and thus the general circulation would play in the occurrence of such events.

The main purpose of our research is to complete the latter study through assessing how extreme temperature may trigger the appearance of high ozone levels and how this concurrence could be linked to the synoptic general circulation. Common impact on human health and wellbeing was also discussed. Our results will bring to light some potential mechanisms that are responsible of heatwaves and air pollution. They may lead to new insights in managing climate extremes and their risk for public health.

2. Experiments

2.1. Study Area

Morocco is located in northwest Africa [5], it is bordered by the Atlantic Ocean to the west, Algeria to the east, Mauritania to the south, and the Mediterranean Sea to the north (Figure 1).

Four mountain ranges dominate the country’s topography and divide it into three geographical regions: the mountainous interior, including fertile plateaus and valleys; the Atlantic coastal lowlands; and the semi-arid and arid areas of eastern and southern Morocco, where the mountains gradually lie down into the Sahara Desert [6].

Casablanca and Marrakech (Figure 1) are two large urban cities in Morocco, where serious pollution concerns may be met. Particularly, significant increase in the cities’ population rates was observed; 11% in Casablanca and 12% in Marrakech between 2004 and 2014. Casablanca is a coastal city and is the first most populous city in Morocco with more than 3,000,000 inhabitants and the highest rate of economic activities. Marrakech is an inland city, it is the fourth largest city in the country with a population of over 900,000 inhabitants [7].

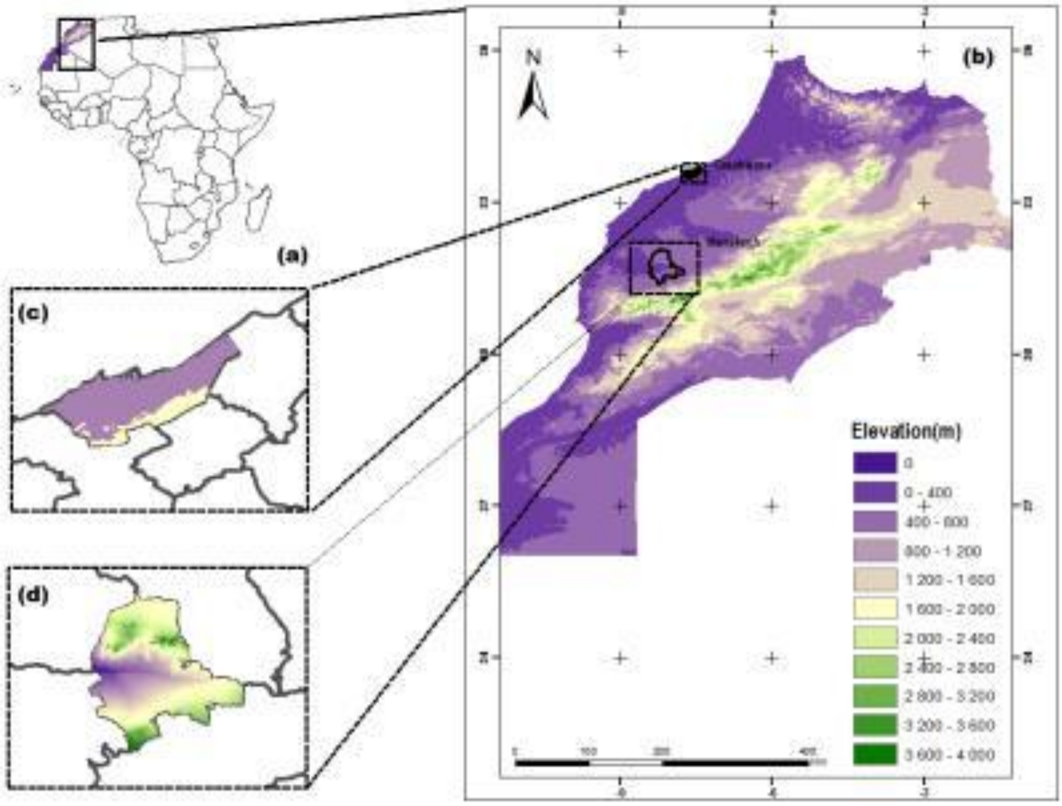

Figure 1. Location of the study area. Africa (a), North Morocco (b), Casablanca (c) and Marrakech (d)

2.2. Data

2.2.1. Temperature and Ozone data

For the purpose of this study, we have used daily maximum temperature and ozone data in Casablanca and Marrakech for the extended summer (April-September) between 2010-2019. This data was provided by the General Directorate of Meteorology in Morocco and is quality controlled before being available.

2.2.1. Climate indexes data

A climate index is a simple diagnostic quantity that is used to characterize an aspect of a geophysical system such as a circulation pattern. For the purpose of this study, three indexes were used. The North Atlantic Oscillation (NAO) Index, the Mediterranean Oscillation (MO) Index and the Saharan Oscillation (SaO) Index.

The pressure centers for the NAO are located in the Atlantic Ocean. This connection consists of a north-south dipole of the Sea Level Pressure (SLP) anomalies, one centered in Greenland and the other in the central North Atlantic [8]. The MO index represents a regional atmospheric circulation that characterizes the Mediterranean basin. It is a model of low frequency variability producing the opposition of barometric, thermal and rainfall anomalies between the extremes of the basin. The Mediterranean Oscillation Index is defined as the difference in geo-potential height anomalies between Algiers and Cairo [9]. The daily data of the NAO and MO indexes during the study period, were collected from the Climatic Research Unit (CRU, http://www.cru.uea.ac.uk/cru/data) website.

The SaO index was first suggested by [7]. It represents the atmospheric circulation that characterizes the Saharan desert in the south of Morocco. It is defined as the difference between the normalized pressure at the Azores (37.79°N, -25.5°E) and the normalized pressure at Niamey

(13.51°N, 2.10°E). For the aim of this work, the SaO was calculated using the formula proposed by the authors [7] :

$$= \quad (\quad) - \quad (\quad), \tag{1}$$

$SaOI_d$: daily Saharan Oscillation Index;
Pn_d: daily normalized pressure during the study period.

The SaO index data was calculated based on the Sea Level Pressure data provided by the ERA5 reanalysis accessible in the Climate Data Store (CDS; https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset).

2.3. Methods

To identify yearly extreme events in temperature and ozone, the 90th percentiles, calculated for each year, were used as thresholds. This thresholding method is widely employed and recommended by the STARDEX (STAtistical and Regional dynamical Downscaling of EXtremes for European regions; http://www.cru.uea.ac.uk/projects/stardex/) and the ETCCDI (Expert Team on Climate Change Detection and Indices; http://cccma.seos.uvic.ca/ETCCDI/) projects. Many studies in Morocco have used this approach as well [5,7,10].

For the purpose of this study, the thresholding approach was applied to summer maximum temperature and ozone data, between 2010 and 2019. The same definitions as in [5] were used:

- A hot event is a day that recorded maximum temperature greater than or equal to the 90th percentile;
- A heat wave is a succession of three hot events or more;
- An extreme ozone (O_3) event is a day that recorded maximum ozone (O_3) greater than or equal to the 90th percentile.

The magnitudes of trends in the studied time series were analyzed using the non-parametric method proposed by Theil and Sen for univariate time series [11,12]. This approach involves computing slopes for all the pairs of ordinal time points and then using the median of these slopes as an estimate of the overall slope. Sen's slope is robust against outliers, it is widely used for the estimation of trending magnitudes of climate series [7,10,13,14]. The statistical significance of the trends is tested using the modified Mann–Kendall test proposed by Hamed and Rao [15] for autocorrelated time series. The test is performed at significance level of 5%.

The percentile thresholds calculated for maximum ozone data time series were compared to the thresholds stated by the Morocco national ambient air quality standards. The later sets ozone (O_3) alert and information thresholds respectively to 200 $\mu g\ m^{-3}$ and 260 $\mu g\ m^{-3}$ for hourly averages.

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 [7,16].

Health impact of concurrent heatwaves and ozone (O3) episodes were assessed through the evaluation of the related Heat Index (HI) and Air Quality Health Index (AQHI). HI as in equation (2), was suggested by [17,18]. It is also known as the apparent temperature and is based upon assumptions about human physiology, behavior, clothing and shade availability.

$$= -42{,}379 + 2{,}04901523 \quad + 10{,}14333127 \quad - 0{,}22475541 \quad \cdots \quad - 0{,}00683783 \quad ^2 - 0{,}05481, \tag{2}$$

HI: Heat Index (in degrees Celsius);
T: Ambient air temperature (in degrees Celsius)
R: Relative humidity (percentage value between 0 and 100)

Table 1 links HI values to the effects on human body.

Table1. Heat Index and impact on human comfort

Temperature (°C)	Impact on human comfort
27-32°C	Caution Fatigue is possible with prolonged exposure and activity. Continuing activity could result heat cramps

32-41°C	Extreme caution: heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
41-54°C	Danger: heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
Over 54°C	Extreme danger: heat stroke is imminent

AQHI as in equation (3), is an index that helps understand the impact of air quality on health. It provides advice on how to improve air quality and pays particular attention to people who are sensitive to air pollution [19].

$$= \left(\frac{1000}{10.4}\right) \times [(0.000537 \times {}_{3} - 1) + (0.000871 \times {}_{2} - 1) + (0.000487 \times {}_{2.5} - 1)], \qquad (3)$$

AQHI: Air Quality Health Index;
O_3: Average concentration of ozone (O_3)
NO_2: Average concentration of nitrogen dioxide
$PM_{2.5}$: Average concentration of particles with a diameter of less than 2.5 µm ($PM_{2.5}$)

Table 2 links AQHI to human health risk.

Table2. Air Quality Health Index and health risk

AQHI	Health Risk
1-3	Low Risk
4-6	Moderate Risk
7-10	High Risk
Above 10	Very High Risk

3. Results

3.1. Trends in extremes of temperature and ozone (O3)

Figure 2 shows the evolution and the trend magnitudes of extreme temperature and ozone (O3) at the studied meteorological and air quality stations, during the summer seasons between 2010 and 2019. The magnitude of the trends in yearly average extreme temperature in the cities of Casablanca and Marrakech are negligible. 2015 and 2012 are the years that recorded the highest temperatures in Casablanca (25.69°C) and Marrakech (34.95°C), respectively. While 2018 has recorded the lowest temperature in both cities.

Extreme ozone (O_3) is decreasing significantly in Casablanca and increasing in Marrakech.

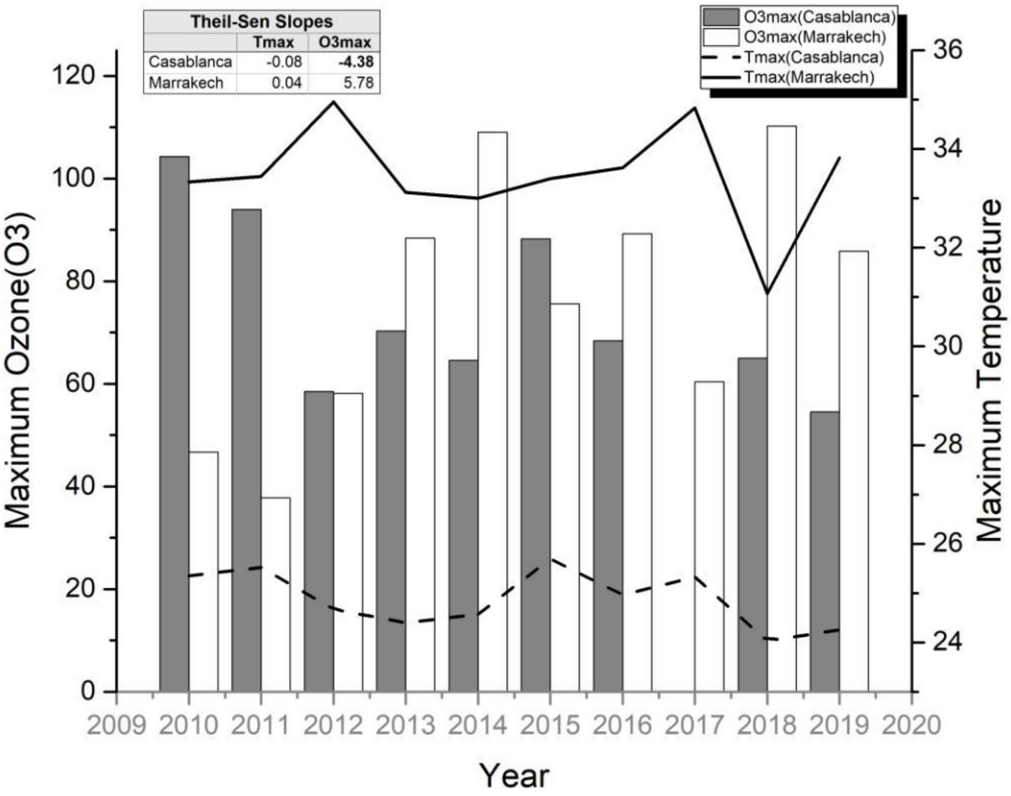

Figure 2. Evolution and trend magnitudes in extreme temperature and ozone, during the summer season between 2010 and 2019. Spearman's coefficient is significant when bold.

3.2. Trends in temperature and ozone (O_3) percentiles

Figure 3 shows the evolution and the trend magnitudes of the 90th percentile of extreme temperature and ozone (O3). Trends in extreme temperature percentiles in the cities of Casablanca and Marrakech are decreasing. Percentiles of extreme ozone (O_3) are decreasing in Casablanca and increasing in Marrakech. None of the trends is statistically significant. Ozone (O3) percentiles still below the national thresholds for hourly averages.

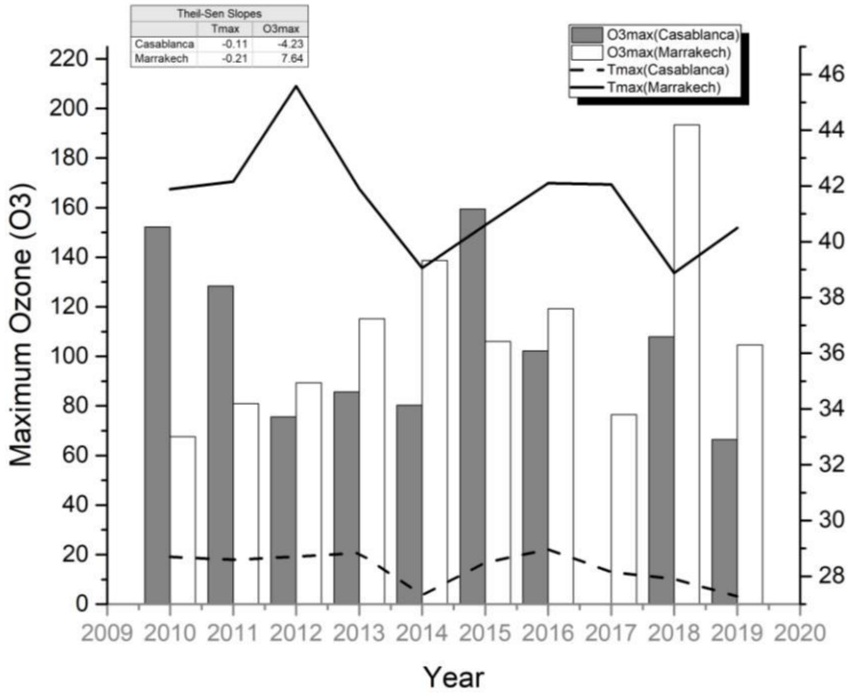

Figure 3. Evolution and trend magnitudes in percentiles in extreme temperature and ozone, during the summer season between 2010 and 2019 Spearman's coefficient is significant when bold.

3.3. Trends in heatwaves and ozone episodes (O3)

Figure 4 shows the evolution and the trend magnitudes of heatwaves and ozone episodes in the cities of Casablanca and Marrakech. Ozone episodes are slightly increasing in Marrakech, meanwhile all the other trends are not statistically significant.

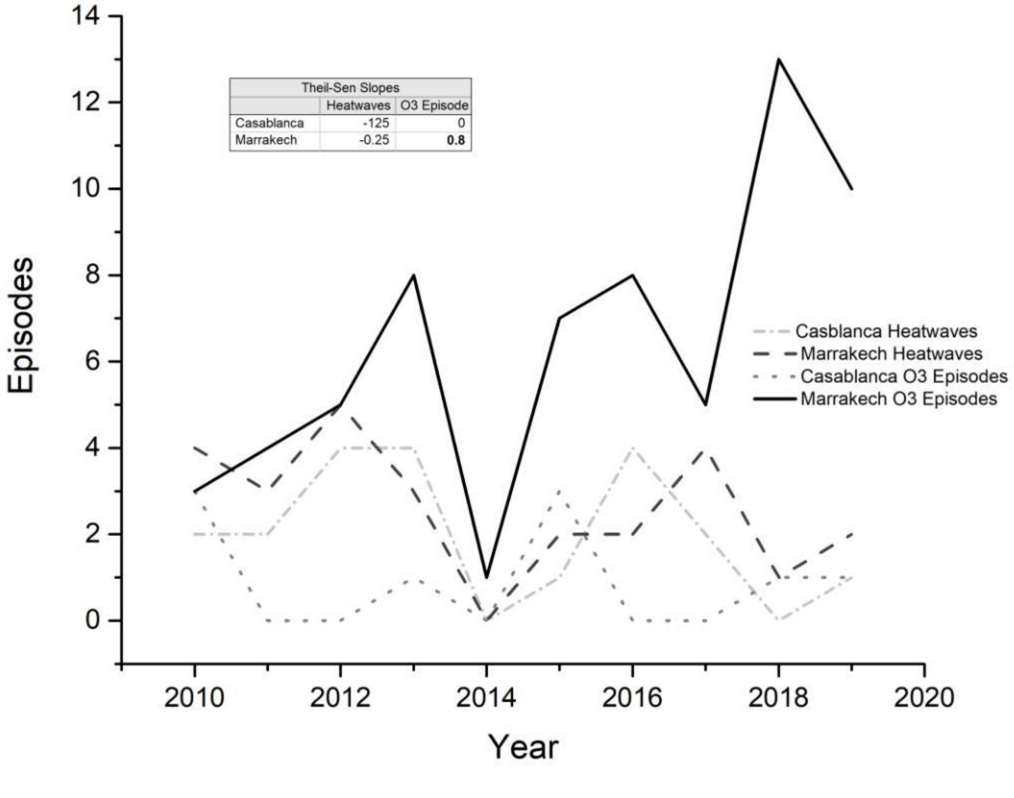

Figure 4. Evolution and trend magnitudes in temperature and ozone episodes, during the summer season between 2010 and 2019. Spearman's coefficient is significant when bold.

3.4. Concurrence of heatwaves and ozone episodes (O3)

The city of Casablanca has recorded 20 heatwaves during the study period, only one heatwave is accompanied with an ozone extreme that also appeared in the city of Marrakech. Marrakech in turn has registered 26 heatwaves, 14 of which was accompanied by ozone episodes. Figure 4 shows the concurrence between heatwaves and ozone episodes. In many cases, ozone extremes match the first day of heatwave or appear slightly offset in time.

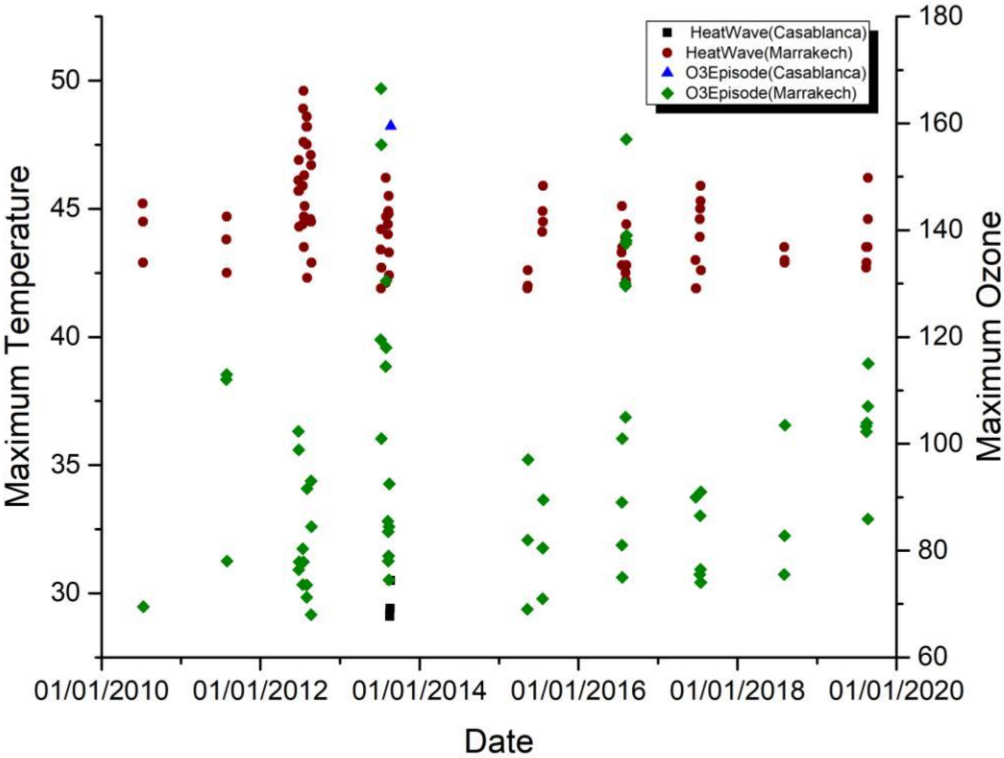

Figure 4. Concurrence between heatwaves and ozone episodes, during the summer season between 2010 and 2019

3.5. Heatwaves and ozone episodes (O3) combiend meteorological patterns

The difference in the occurrence of extreme episodes between Casablanca and Marrakech may be due to the impact of meteorological patterns and geographical location knowing that Casablanca is a coastal city and Marrakech is inland. In this paragraph, we investigate the relationship of observed maximum temperature and ozone (O_3) with humidity in one hand and with the above defined climate indexes (NAO, MO and SaO) in the other hand. This work is performed in both Casablanca and Marrakech. Graphs and spearman coefficients in figures 5 and 6 show that significant relationships, yet very weak in many cases, exist between extreme ozone in both cities, humidity and climate indexes. Maximum ozone in Casablanca is negatively correlated with NAO index and positively correlated with the remaining parameters. Meanwhile in Marrakech, correlation is negative with humidity and positive for the other factors. Correlation between maximum temperature and humidity in Marrakech is negative and quite strong. Positive, moderate and significant correlations appear between maximum temperature and MO index in both cities. Correlations of the same order, yet negative, appear between maximum temperature and SaO.

In parallel to this analysis, SLP field for the only registered common heatwave and ozone episode recorded in both cities were redrawn to analyze the flow impacting the study area at the large scale. This event lasts 5 days in Casablanca (August 09th, 2013 to August 13th, 2013) and 7 days in Marrakech (August 09th, 2013 to August 15th, 2013). Ozone episodes appear slightly offset in time in Casablanca (August 17th, 2013 to August 22th, 2013) and in the same period in Marrakech (August 09th, 2013 to August 13th, 2013). According to the SLP field redrawn in Figure 7, the country is under the combined influence of the Azores High, spreading over the Atlantic and the Western Europe, and the Saharan trough extending the depression centered in the south. This trough invades the country, reach the south of the European continent and generates a warm southern flow over the region.

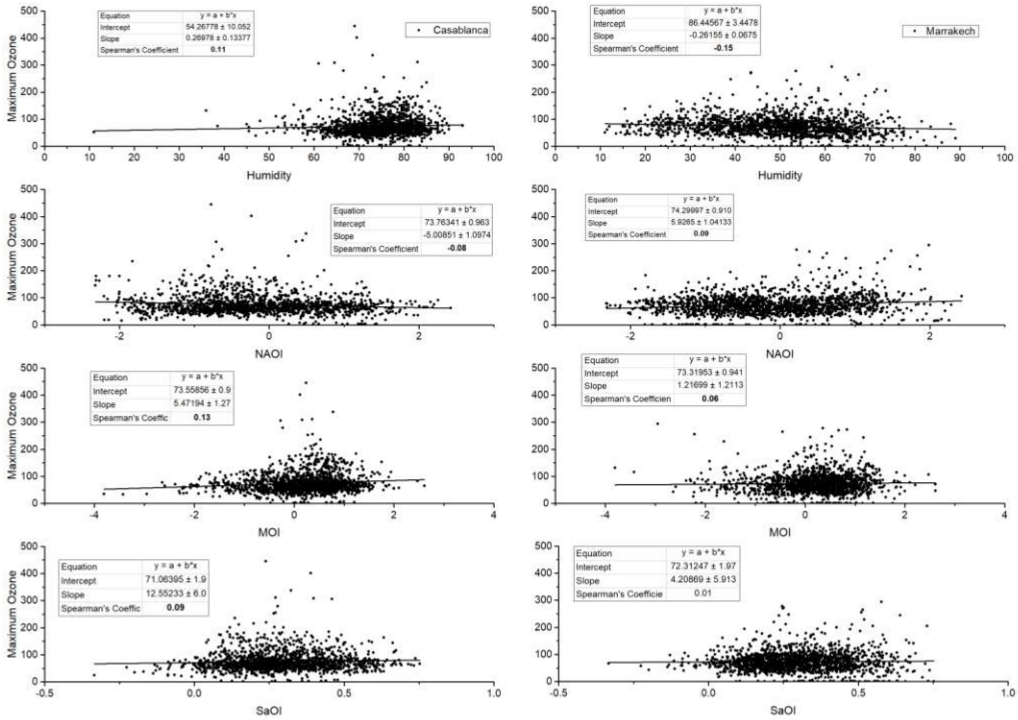

Figure 5. Correlation between extreme ozone, humidity and climate indexes, during the summer season between 2010 and 2019. Spearman's coefficient is significant when bold.

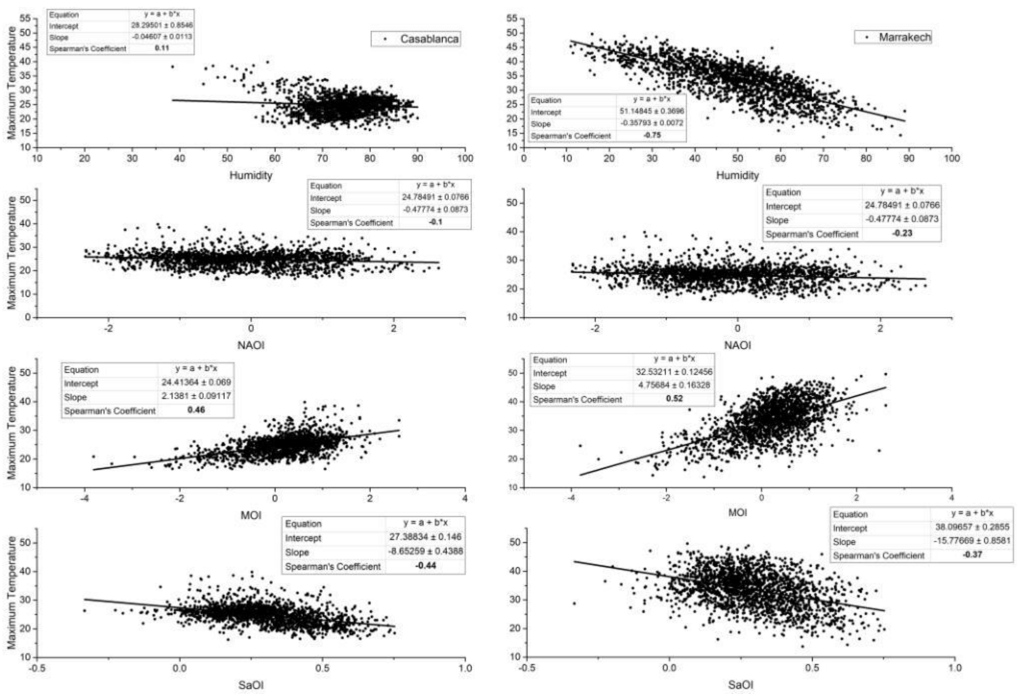

Figure 6. Correlation between maximum temperature, humidity and climate indexes, during the summer season between 2010 and 2019. Spearman's coefficient is significant when bold.

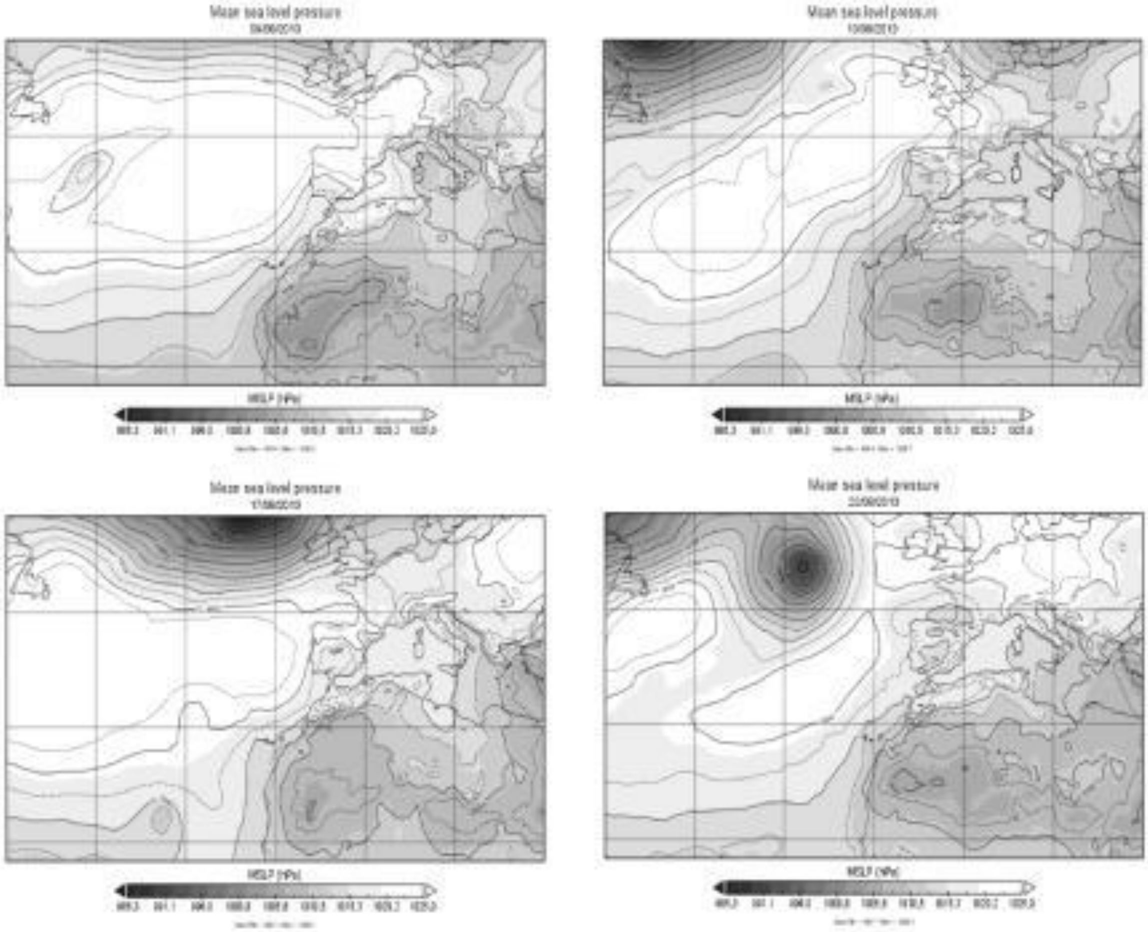

Figure 7. SLP fields for the 08-13-17-22/08/2013

3.6. Impact of concurrent heatwaves and ozone episodes (O3) on human health

Table 3 shows HI and AQHI that were assessed for the heatwave and the ozone episode period that occurred between August 09th, 2013 and August 22th, 2013, in Casablanca and Marrakech. Marrakech tends to register more heat alerts than Casablanca. Hot days recorded in Casablanca didn't alert to any heat risk meanwhile the city registered a day with very high risk and 5 days with high risk caused by unhealthy air quality levels. Marrakech recorded 5 days with combined extreme heat warning and high risk of unhealthy air quality which may have a joined impact on human respiratory health and thermal comfort.

Table3. Heat and Air Quality Health indexes between August 09th, 2013 and August 22th, 2013, in Casablanca and Marrakech

Days of the episode	**Casablanca**		**Marrakech**	
	Heat Risk	**Air Quality Risk**	**Heat Risk**	**Air Quality Risk**
August 09th, 2013	No Risk	**High Risk**	**Extreme Caution**	**High Risk**
August 10th, 2013	No Risk	**High Risk**	**Extreme Caution**	**High Risk**
August 11th, 2013	No Risk	**Very High Risk**	Extreme Caution	Moderate Risk
August 12th, 2013	No Risk	**High Risk**	Extreme Caution	Moderate Risk
August 13th, 2013	No Risk	Moderate Risk	**Extreme Caution**	**High Risk**
August 14th, 2013	No Risk	Moderate Risk	Extreme Caution	Moderate Risk
August 15th, 2013	No Risk	Moderate Risk	**Extreme Caution**	**High Risk**
August 16th, 2013	No Risk	Moderate Risk	Caution	High Risk
August 17th, 2013	No Risk	Moderate Risk	No Risk	Moderate Risk

August 18th, 2013	No Risk	Moderate Risk	Caution	High Risk
August 19th, 2013	No Risk	**High Risk**	Caution	High Risk
August 20th, 2013	No Risk	**High Risk**	**Extreme Caution**	**High Risk**
August 21th, 2013	No Risk	Moderate Risk	Caution	High Risk
August 22th, 2013	No Risk	Moderate Risk	Caution	Moderate Risk

4. Discussion

In this study we used observed data during the extended summer (April-September) between 2010 and 2019, in two cities from Morocco, Casablanca and Marrakech. We analysed their trends and their correlations with atmospheric indexes. We identified heatwaves and ozone (O_3) episodes and analysed their concurrence. We identified the atmospheric patterns behind this concurrence and the possible combined impacts on human health. Taken together, our results suggest that during the study period:

- No trends were recognized in average extreme temperature in both cities. This finding doesn't reinforce the general results of warmer trends in the country [10,20–22] and may be due to the short used study period or to the consideration of more recent data. Indeed, 2018 data was considered; this year has recorded the lowest temperature in both cities and was characterized with below normal winter temperatures and snowfall in the country [23]. This may have affected the expected warming trend.

Extreme ozone (O_3) is decreasing significantly in Casablanca and increasing in Marrakech. This may be due to the different geographical positions of the cities and the various local characteristics of outdoor pollution in each city. Casablanca is coastal, it plays a leading role in the economic development of Morocco. It hosts various industrial activities, an important automobile park, energy production and distribution and the country's largest ports and airport [24,25]. Considering its geographical position, Casablanca still underexposed to sunlight and even if it may register high NO_2 and VOCs concentration levels, the photochemical pollution is not its main feature. Moreover, Casablanca Tramway implementation in 2012 has played an important role in reducing NO_2 emissions and then ozone (O_3) generation. Marrakech, an inland city, hosts weak industrial activities and a rather important density of vehicles causing high NO_2 concentrations levels. This makes the city a subject to photochemical pollution mainly due to its geographical location inducing strong sunlight. During spring and summer, ozone (O_3) concentrations in the city reach alarming levels and exceed the thresholds [26,27].

- Trends in temperature and ozone (O_3) percentiles and extreme events echo the trends in averages. Extreme events may be partly explained by averages. This statement is in complete agreement with many other climatological and air pollution studies over the area [5,10,20,28].
- Concurrence of heatwaves and ozone (O_3) episodes in both cities were not systemic. Yet, when it happens, ozone (O_3) episodes appear either in the first day of the heatwave or slightly offset in time. Marrakech recorded more concurring events than Casablanca. This spotlights the role of the geographical location of the cities and the influence of meteorological parameters, mainly humidity, on events' occurrence. This influence was highlighted in many previous studies as well [1,4,5,29]. For example, [29] concluded that

soaring ozone concentrations across China in 2017 could be mainly attributed to the notable change of meteorological conditions in 2017, characterized with rising temperature and sunshine duration and decreasing humidity. This finding explains the correlations between extreme ozone (O_3) and humidity in Casablanca (positive) and Marrakech (negative) and clarifies the strong negative correlation between maximum temperature and humidity in Marrakech.

- Positive, moderate and significant correlations appear between maximum temperature and MO index in both cities. Negative correlations of the same order appear with the SaO index. This finding recalls results from [10] and [7]. [10] confirms that summer average maximum temperature is affected by the MO in Marrakech. [7] elucidates the relationship between the MO and the average concentrations of particulate matter 10 micrometers or less in diameter (PM10) and confirms that MO and SaO are affecting the particulate pollution oppositely. The northeasterly to southwesterly continental warm flow that is triggered by the Saharan trough and influenced by the high-pressure area in the north causes the temperature to increase and foster particulate pollution. If extended, the high-pressure area in the north of Morocco can create a blocking situation and induce photochemical pollution as well.
- We expected stronger correlations between maximum ozone (O_3), humidity and climate indexes. The found weak links may be due to the local features of photochemical pollution in both cities and the continuous supply of local primary pollutants (NO_x and COVs) from the large vehicle fleet in both cities or from industrial activities in Casablanca. Moreover, this study was conducted in the extended summer when sunshine duration is the main factor responsible of ozone (O_3) generation.
- The case study of the heatwave from August 09th, 2013 to August 22th, 2013 confirmed the above findings. Ozone episodes appear slightly offset in time in Casablanca and in the same period in Marrakech. The country was under the combined influence of the Azores High, spreading over the Atlantic and the Western Europe, and the Saharan trough extending the depression centered in the south. This trough invades the country, reach the south of the European continent and generates a warm southern flow over the region. This synoptic pattern explains the correlations between maximum temperatures and MO and SaO indexes and explicates the role of the anticyclonic area over the north of Morocco in trapping the warm air over the country or allowing it to attend the European continent.
- During the above-mentioned case study, combined risk on human health and thermal comfort was registered mainly in Marrakech. Humidity in the coastal city of Casablanca reduced the heat risk, yet, the high risk of unhealthy air quality levels was registered. If available, exposure data can help in further developing this aspect.

The analysis in this study examines heatwaves and ozone (O3) episodes in Casablanca and Marrakech and therefore the results are limited to these regions that have their own geographical locations and climate conditions. The results are also limited to the study period and the methods used, especially to identify extreme events. Further studies are worth to be conducted, when data are available, to cover more regions, include other atmospheric indexes such us ENSO or SaO in different pressure levels or extend the temporal coverage in the future. Heat and air pollution related mortality and morbidity data are worth to be considered, when available, to study in depth the combined impact of heatwaves and air pollution episodes on human health and well-being.

5. Conclusions

This work has focused on the study of the concurrence of heatwaves and ozone (O_3) episodes, their relationship with atmospheric circulation indexes and their combined impact on human health and well-being. It was carried out, in two cities from Morocco: Casablanca and Marrakech, during the summer season between 2010 and 2019.

The research doesn't support the simple mechanistic argument stipulating that warmer temperatures make ozone pollution more severe. It confirms that the concurrence of heatwaves and ozone episodes depends both on the specific city—hence, local sources—and on large-scale atmospheric circulation —thus, meteorological parameters, mainly humidity. The study identified the likely synoptic pattern behind the occurrence of these events. This pattern and related meteorological factors can be linked to direct health effects.

When more data becomes available, the contribution from local and global pollution sources may be estimated. This emphasizes the need for more local to regional studies. It would be worthwhile making such a study for other regions in Morocco and considering other pollutants. Obtained results could then be compared with those of the present study.

Although many previous researches have examined air pollution in Casablanca and Marrakech, our study is the first attempt to assess combined features inducing large-scale atmospheric circulation and health effects. Our work explores the hypothesis that particular weather patterns increase the vulnerability of individuals especially those sensitive to air pollution. Additional studies may aid the establishment of an alert system and provide recommendations for coping with concurrent heatwaves and air pollution episodes.

Author Contributions: Conceptualization, Kenza Khomsi, Youssef Chelhaoui , Houda Najmi and Zineb Souhaili; Data curation, Kenza Khomsi, Youssef Chelhaoui , Soukaina Alilou, Rania Souri and Houda Najmi; Formal analysis, Kenza Khomsi, Youssef Chelhaoui , Soukaina Alilou, Rania Souri and Houda Najmi; Funding acquisition, Soukaina Alilou; Investigation, Kenza Khomsi, Youssef Chelhaoui , Soukaina Alilou, Rania Souri and Houda Najmi; Methodology, Kenza Khomsi, Youssef Chelhaoui , Soukaina Alilou, Rania Souri, Houda Najmi and Zineb Souhaili; Project administration, Kenza Khomsi, Soukaina Alilou and Rania Souri; Resources, Kenza Khomsi, Youssef Chelhaoui , Soukaina Alilou and Rania Souri; Software, Kenza Khomsi, Youssef Chelhaoui , Rania Souri and Houda Najmi; Validation, Kenza Khomsi, Youssef Chelhaoui and Zineb Souhaili; Visualization, Kenza Khomsi, Youssef Chelhaoui , Soukaina Alilou and Rania Souri; Writing – original draft, Kenza Khomsi; Writing – review & editing, Zineb Souhaili.

Funding: This research received no external funding.

Acknowledgments: The authors wish to express their thanks for the support of the General Directorate of Meteorology that made meteorology and air quality data available for the present study. These data are not publicly available, data requests must be addressed to the providing organization.

Conflicts of Interest: The authors declare no conflict of interest.

References

1.Lin, X.; Yuan, Z.; Yang, L.; Luo, H.; Li, W. Impact of extreme meteorological events on ozone in the pearl river delta, China. *Aerosol Air Qual. Res.* **2019**, doi:10.4209/aaqr.2019.01.0027.

2.Utembe, S. R.; Rayner, P. J.; Silver, J. D.; Guérette, E. A.; Fisher, J. A.; Emmerson, K. M.; Cope, M.; Paton-Walsh, C.; Griffiths, A. D.; Duc, H.; Monk, K.; Scorgie, Y. Hot summers: Effect of extreme temperatures on ozone in Sydney, Australia. *Atmosphere (Basel).* **2018**, doi:10.3390/atmos9120466.

3.Chiquetto, J. B.; Silva, M. E. S.; Cabral-Miranda, W.; Ribeiro, F. N. D.; Ibarra-Espinosa, S. A.; Ynoue, R. Y. Air quality standards and extreme ozone events in the São Paulo megacity. *Sustain.* **2019**, doi:10.3390/su11133725.

4.Otero, N.; Sillmann, J.; Schnell, J. L.; Rust, H. W.; Butler, T. Synoptic and meteorological drivers of extreme ozone concentrations over Europe. *Environ. Res. Lett.* **2016**, doi:10.1088/1748-9326/11/2/024005.

5.Khomsi, K.; Najmi, H.; Souhaili, Z. Co-occurrence of extreme ozone and heat waves in two cities from Morocco. *Satell. Oceanogr. Meteorol.* **2018**, doi:10.18063/som.v3i3.733.

6.Hssaisoune, M.; Bouchaou, L.; Sifeddine, A.; Bouimetarhan, I.; Chehbouni, A. Moroccan groundwater resources and evolution with global climate changes. *Geosci.* **2020**, doi:10.3390/geosciences10020081.

7.Khomsi, K.; Najmi, H.; Chelhaoui, Y.; Souhaili, Z. The contribution of large-scale atmospheric patterns to pm10 pollution: The new saharan oscillation index. *Aerosol Air Qual. Res.* **2020**, doi:10.4209/aaqr.2019.08.0401.

8.Cassou, C. Du changement climatique aux régimes de temps : l ' oscillation nord-atlantique. *La Météorologie* **2004**.

9.Martin-Vide, J.; Lopez-Bustins, J. A. The Western Mediterranean Oscillation and rainfall in the Iberian Peninsula. *Int. J. Climatol.* **2006**, doi:10.1002/joc.1388.

10.Khomsi, K.; Mahe, G.; Tramblay, Y.; Sinan, M.; Snoussi, M. Regional impacts of global change: Seasonal trends in extreme rainfall, run-off and temperature in two contrasting regions of Morocco. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 1079–1090, doi:10.5194/nhess-16-1079-2016.

11.Theil, H. A rank-invariant method of linear and polynomial regression analysis. I. *Nederl. Akad. Wetensch., Proc.* **1950**, *53*, 386–392, doi:10.1007/978-94-011-2546-8.

12.Sen, P. K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379, doi:10.2307/2285891.

13.Kahsay, K. D.; Pingale, S. M.; Hatiye, S. D. Impact of climate change on groundwater recharge and base flow in the sub-catchment of Tekeze basin, Ethiopia. *Groundw. Sustain. Dev.* **2018**, doi:10.1016/j.gsd.2017.12.002.

14.Byakatonda, J.; Parida, B. P.; Kenabatho, P. K.; Moalafhi, D. B. Analysis of rainfall and temperature time series to detect long-term climatic trends and variability over semi-arid Botswana. *J. Earth Syst. Sci.* **2018**, doi:10.1007/s12040-018-0926-3.

15.Hamed, K. H.; Ramachandra Rao, A. A modified Mann-Kendall trend test for autocorrelated data. *J. Hydrol.* **1998**, *204*, 182–196, doi:10.1016/S0022-1694(97)00125-X.

16.Méndez-Lázaro, P.; Muller-Karger, F. E.; Otis, D.; McCarthy, M. J.; Peña-Orellana, M. Assessing climate variability effects on dengue incidence in San Juan, Puerto Rico. *Int. J. Environ. Res. Public Health* **2014**, doi:10.3390/ijerph110909409.

17.Steadman, R. G.; Steadman, R. G. The Assessment of Sultriness. Part II: Effects of Wind, Extra

Radiation and Barometric Pressure on Apparent Temperature. *J. Appl. Meteorol.* **1979**, doi:10.1175/1520-0450(1979)018<0874:TAOSPI>2.0.CO;2.

18.Steadman, R. G.; Steadman, R. G. The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science. *J. Appl. Meteorol.* **1979**, doi:10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2.

19.Stieb, D. M.; Burnett, R. T.; Smith-Doiron, M.; Brion, O.; Hwashin, H. S.; Economou, V. A new multipollutant, no-threshold air quality health index based on short-term associations observed in daily time-series analyses. *J. Air Waste Manag. Assoc.* **2008**, doi:10.3155/1047-3289.58.3.435.

20.Filahi, S.; Tanarhte, M.; Mouhir, L.; El Morhit, M.; Tramblay, Y. Trends in indices of daily temperature and precipitations extremes in Morocco. *Theor. Appl. Climatol.* **2016**, doi:10.1007/s00704-015-1472-4.

21.Donat, M. G.; Peterson, T. C.; Brunet, M.; King, A. D.; Almazroui, M.; Kolli, R. K.; Boucherf, D.; Al-Mulla, A. Y.; Nour, A. Y.; Aly, A. A.; Nada, T. A. A.; Semawi, M. M.; Al Dashti, H. A.; Salhab, T. G.; El Fadli, K. I.; Muftah, M. K.; Dah Eida, S.; Badi, W.; Driouech, F.; El Rhaz, K.; Abubaker, M. J. Y.; Ghulam, A. S.; Erayah, A. S.; Mansour, M. Ben; Alabdouli, W. O.; Al Dhanhani, J. S.; Al Shekaili, M. N. Changes in extreme temperature and precipitation in the Arab region: Long-term trends and variability related to ENSO and NAO. *Int. J. Climatol.* **2014**, *34*, 581–592, doi:10.1002/joc.3707.

22.Driouech, F.; Stafi, H.; Khouakhi, A.; Moutia, S.; Badi, W.; ElRhaz, K.; Chehbouni, A. Recent observed country-wide climate trends in Morocco. *Int. J. Climatol.* **2020**, doi:10.1002/joc.6734.

23. Https://reliefweb.int/ Morocco: Cold Wave - Jan 2018 Available online: https://reliefweb.int/disaster/cw-2018-000008-mar.

24.Khadija, H.; Lahcen, B. The Carbon monoxide (CO) contribution in the air pollution case of the Greater Casablanca Region, Morocco. *J. Ind. Pollut. Control* **2017**.

25.Inchaouh, M.; Tahiri, M. Air pollution due to road transportation in Morocco : evolution and impacts. **2017**, *4*.

26.Inchaouh, M. STATE OF AMBIENT AIR QUALITY IN MARRAKECH CITY (MOROCCO) OVER THE PERIOD 2009 – 2012. *Int. J. GEOMATE* **2016**, doi:10.21660/2017.29.1254.

27.Ouarzazi, J.; Terhzaz, M.; Abdellaoui, A.; Bouhafid, A.; Nollet, V.; Dechaux, J.-C. Etude descriptive de la mesure de polluants atmosphériques dans l'agglomération de Marrakech. *Pollut. atmosphérique* **2003**, doi:10.4267/pollution-atmospherique.1937.

28.Tramblay, Y.; Badi, W.; Driouech, F.; El Adlouni, S.; Neppel, L.; Servat, E. Climate change impacts on extreme precipitation in Morocco. *Glob. Planet. Change* **2012**, *82–83*, 104–114, doi:10.1016/j.gloplacha.2011.12.002.

29.Chen, Z.; Li, R.; Chen, D.; Zhuang, Y.; Gao, B.; Yang, L.; Li, M. Understanding the causal influence of major meteorological factors on ground ozone concentrations across China. *J. Clean. Prod.* **2020**, doi:10.1016/j.jclepro.2019.118498.