RESEARCH ARTICLE

Co-occurrence of extreme ozone and heat waves in two cities from Morocco

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Abstract: Temperature is the first meteorological factor to be directly involved in leading ozone (O3) extreme events. Generally, upward temperatures increase the probability of having exceedance in ozone adopted thresholds. In the global climate change context more frequent and/or persistent heat waves and extreme ozone (O3) episodes are likely to occur during in coming decades and a key question is about the coincidence and co-occurrence of these extremes. In this paper, using 7 years of surface temperature and air quality observations over two cities from Morocco (Casablanca and Marrakech) and implementing a percentile thresholding approach, we show that the extremes in temperature and ozone (O3) cluster together in many cases and that the outbreak of ozone events generally match the first or second days of heat waves. This co-occurrence of extreme episodes is highly impacted by humidity and may be overlapping large-scale episodes.

Keywords: Heat Wave; Extreme Ozone (O3) Event; Percentiles; Co-occurrence; Morocco

1. Introduction

When combined, pollution and weather extremes are highly suspected to cause greater human health impacts[1–3]. Furthermore, the current scientific consensus agrees that climate change will change the intensity and frequency of extreme events in weather and air pollution that will worsen under future climate change.

Heat waves are defined as summer hot episodes, recording high surface air temperatures that last several days[4]. Meteorologists consider that these type of episodes are basically associated with particular atmospheric patterns that occur under anticyclonic hot conditions and characterized with clear skies and prolonged elevated temperatures in the near surface layer[5]. Humans health, efficiency and wellbeing are significantly impacted with heat waves that are considered among the most threatening natural hazards[6,7]. They can remarkably increase rates in morbidity and mortality mainly in populated cities[8,9].

Surface ozone (O3), one of the most important air pollutants threatening human health[10,11], is a secondary trace gas in the atmosphere, it is not directly emitted from any natural or anthropogenic sources but rather formed through a complex set of nonlinear chemical reactions involving, mainly, nitrogen oxides (NOx) and volatile organic compounds (VOCs) under the influence of sunlight. Like heat waves, extreme ozone episodes are often driven by synoptic meteorology, they typically occur under a slow-moving high-pressure system, which brings abundant solar insolation, warm temperatures, light wind speeds, and little to no precipitation[12].

Specific and common meteorological drivers may be beyond the occurrence and the coincidence of hot temperature and ozone extremes; this can theoretically exacerbate their effects over and above their own and individual impacts.

Apart from the meteorological effect which is direct, both extreme conditions (temperature and ozone) are worsened under the influence of other feedbacks and interactions. Examples from the scientific literature mention the increasing in the surface O3 production as a result of the increasing of the volatile organic components emission rates, the inhibition of the O3 stomatal uptake caused by the drought-like conditions which frequently follow heat waves[13] and the impact on soil moisture; these interactions are favorable to negative heat waves and bad air quality impacts[14]. Anyhow, the common underlying conditions cause extremes to co-occur and increase risks on human health[12].

Actually, the need to study the coincidence of temperature and air pollution extremes, mainly those related to ozone (O3), was brought to the forefront of the climate change community following the extreme pollution episode and heat wave over Europe in 2003 that resulted in thousands of deaths[12] and emphasized the need of analyzing the co-occurrence of these extremes in order to better understand and handle their joint effects on human health.

In Morocco, most of existing scientific studies on climate were focused on the ordinary variables like precipitation

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amounts and average temperatures, some on rainfall and temperature extreme events[15–17] but less on the increasingheat waves and their relationship with high levels of surface ozone (O3)

In this paper, using 7 years of temperature and air quality observations over two known cities from Morocco: Casablanca and Marrakech, we assess the evolution of two type of extremes: surface ozone (O3) extremes and heat waves and their co-occurrence between 2009 and 2016; this period was chosen with respect to the availability of ozone (O3) data. The analysis was limited to the extended summer season (April–September) since the majority of heat waves in Morocco occur during the warm season.

Casablanca and Marrakech are, respectively, the first and the forth populous cities in the country with, respectively, 3.359.818 and 928.850 residents according to the census of 2014[18]. These two cities were chosen as the study area where extreme hot events are particularly serious because of the typical subtropical climate on one hand and the urban heat island effect since the population increased by about 11% in Casablanca and 12% in Marrakech be-tween 2004 and 2014, on the other hand.

2. Study area, data and methods

2.1 Study area

Morocco is the most north-western country in Africa (**Figure 1**). It is located in the southern part of the Mediterranean region and is considered among the most vulnerable countries with respect to climate variability, especially with a possible increased frequency of extreme events[15,19].

Casablanca is a coastal city, the largest city in Morocco, located in the central-western part of the country bordering the Atlantic Ocean (**Figure 1**). It is the largest city in the Maghreb, as well as one of the largest and most important cities in Africa, both economically and demographically.

Marrakech is a major city of the Kingdom of Morocco. It is the fourth largest city in the country, after Casablanca, Fez and Tangier. It is the capital city of the mid-southwestern region of Marrakesh-Safi and is an inland city, located to the north of the foothills of the snow-capped Atlas Mountains (**Figure 1**).

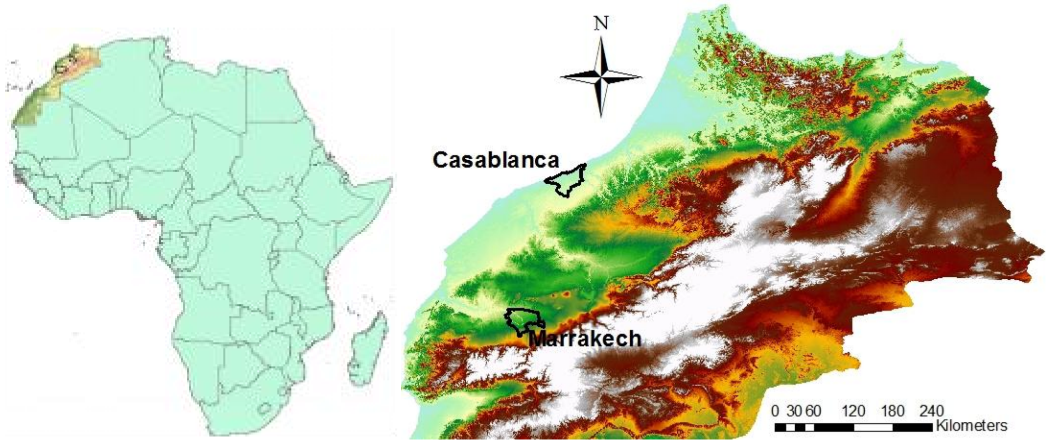

Figure1. Location of Morocco in Africa (up left map) and location of the cities of Casablanca and Marrakech in Morocco

2.2 Data

Daily Maximum temperature and ozone (O3) data were collected, respectively, from the two meteorological stations of Casablanca and Marrakech and the four air quality stations of Zrektouni and Ain Sebaa in Casablanca and Jamaa Lafna and Lmhamid in Marrakech (**Figure 2**). These stations are managed by the Moroccan Meteorological Office (Direction de la Météorologie Nationale – DMN). All of the collected data underwent quality control before being publicly available; meteorological data control is performed according to the recommendations of the World Meteorological Organization[20] while air quality control is performed according to the rules and recommendations from the Agency for the Environment and Energy Management[21].

Taking account of ozone (O3) data availability, this study was performed on the extended summer (April-September) data from 2009 to 2016.

Ozone (O3) measurement station

Figure 2. Ozone (O3) measurement stations in Casablanca and Marrakech.

2.2 Methods

To identify extreme events in temperature and ozone, the 90th and 95th percentiles computed across the whole-time period were used as thresholds, as they are 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. This approach was applied to summer maximum temperature and ozone data, between 2009 and 2016. The following definitions were used:

A hot event is a day that recorded maximum temperature greater than or equal to the 95th percentile;

A heat wave is a succession of three hot events or more;

An extreme ozone (O3) event is a day that recorded maximum ozone (O3) greater than or equal to the 90th percentile.

The magnitudes of trends in time series were analyzed using the non-parametric method proposed by Theil and Sen[22,23] for univariate time series. 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. Since Sen's slope is robust against outliers, it is widely used for the estimation of trending magnitudes of climate series[24–28]. The statistical significance of the obtained trends is tested using the modified Mann– Kendall test proposed by Hamed and Rao[29] 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 (O3) alert and information thresholds respectively to 200 µg m^{-3} and 260 µg m^{-3} for hourly averages.

3. Results and discussion

3.1 Trends in average temperature and ozone (O3) extremes

According to the data collected and the statistical approach used, Table 1 and **Figure 3** show the evolution and the trend magnitudes for average extreme temperature and ozone (O3) at the studied meteorological and air quality stations, during the summer seasons between 2009 and 2016.

The magnitude of the trends in yearly average extreme temperature in the cities of Casablanca and Marrakech are weak to negligible. 2012 is the year that recorded the highest temperature in Marrakech. While 2014 has recorded the lowest temperature in both cities.

Trends in annual extreme ozone (O3) are slightly increasing in Jamaa Lafna and Zrektouni and slightly decreasing in Lmhamid and Ain Sebaa. None of the trends is statistically significant.

Station	Average Maximum temperature	Average Extreme ozone (O3)
Marrakech	0,01	-
Casablanca	-0,01	-
Jamaa Lafna	-	0,33
Lmhamid	-	-0,66
Zrektouni	-	0,46
Ain Sebaa	-	-2,29

Table 1. Annual trends in average extreme temperature and ozone (O3) in the studied area; significance level=0.05

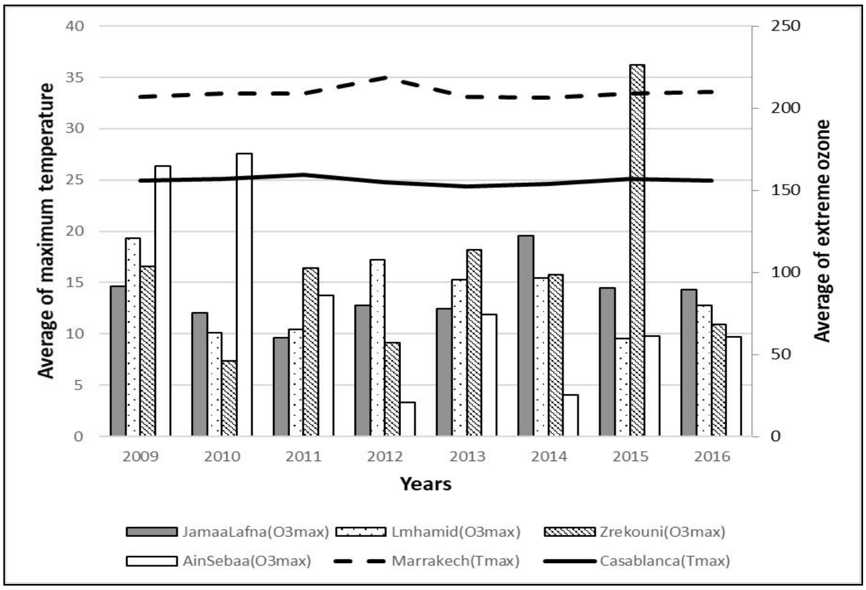

Figure 3. Evolution of average extreme temperature and ozone in the studied area during the summer season between 2009 and 2016 (O3max: Average extreme ozone, O3max: Average extreme temperature)

3.2 Trends in heat waves and extreme ozone (O3) events

According to the data collected and the statistical approach used, Table 2 and **Figure 4** show the evolution and the trend magnitudes for heat waves and single extreme temperature and ozone (O3) events at the studied meteorological and air quality stations, during the summer seasons between 2009 and 2016.

The magnitude of the trends in extreme temperature events in the cities of Casablanca and Marrakech are weak to negligible. 2012 is the year that recorded the most important number of single temperature hot events and heat waves in both cities while 2014 has recorded the lowest number.

Trends in extreme ozone (O3) events are slightly increasing in Jamaa Lafna and Zrektouni and slightly decreasing in Lmhamid and Ain Sebaa. The downward trend in the later station is statistically significant.

Station	Trends		
	Extreme temperature events	Hot waves	Extreme ozone (O3) events
Marrakech	-0,12	-0,03	-
Casablanca	0	0	-
Jamaa Lafna	-	-	0,16
Lmhamid	-	-	-0,16
Zrektouni	-	-	0,14
Ain Sebaa	-	-	-0,12[1]

Table 2. Annual trends in hot waves and extreme temperature and ozone (O3) events in the studied area; significance level=0.05

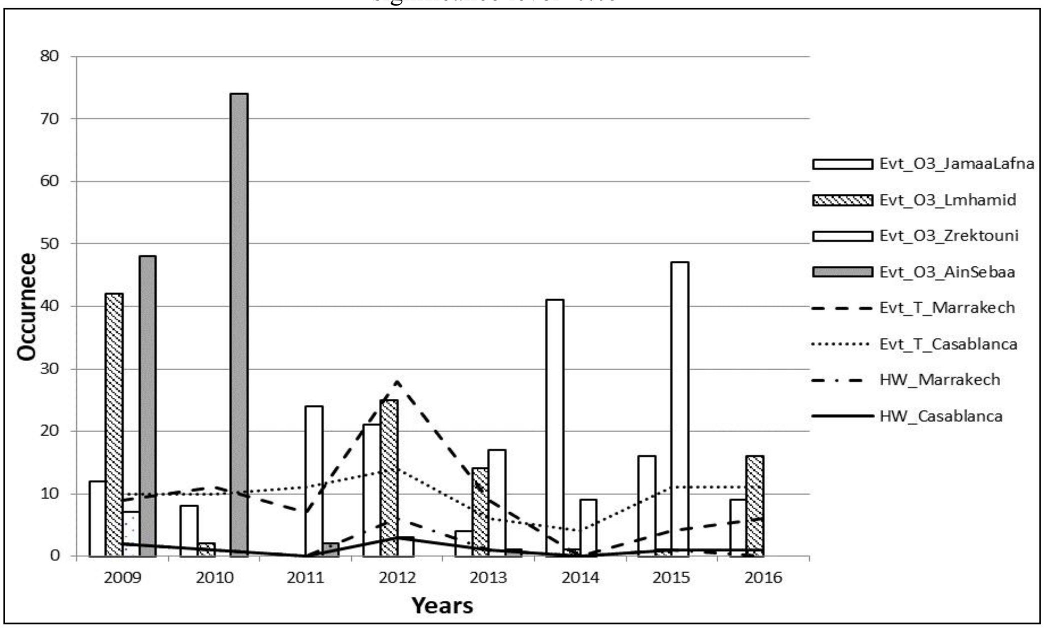

Figure 4. Evolution of heat waves and extreme O3 events in the studied area during the summer season between 2009 and 2016 (Evt_O3: extreme ozone events, Evt_T: extreme temperature events, HW: heat waves).

3.3 Co-occurrence of heat waves and ozone (O3) events

Scatterplots of summer co-occurrence of extreme temperature and ozone events were addressed for all measurement stations between 2009 and 2016. Figures 5 and 6 draw these scatterplots prepared for the areas of Marrakech and Casablanca respectively.

During the summer of 2009, the meteorological station of Marrakech has recorded 9 hot events and 2 heat waves while the station of Casablanca has recorded 10 hot events and the same number of heat waves. Heat waves in both cities were accompanied with extreme ozone events matching their first days for three cases and the second day for one case. In the city of Marrakech, these ozone events were recorded mainly in Lmhamid while in Casablanca they have occurred in Ain Sebaa. Other extreme ozone events don't coincide with any overrun of the 95th percentile of maximum temperatures. Many recorded ozone events coincide in the two studied cities even if not trigged by extreme hot events.

The summer of 2012 has recorded the most important number of heat waves, 6 in Marrakech and 3 in Casablanca. 4 of the heat waves recorded in Marrakech were accompanied with 5 single extreme ozone (O3) events in Jamaa Lafna and 5 in Lmhamid. The starting of Most of the registered ozone events matches the first or the second days of the heat waves. No ozone events were recorded in Casablanca.

During the summers of 2010 and 2013, each city has recorded one yearly heat wave and they were accompanied with no extreme ozone events.

In 2011 and 2014, no heat waves were recorded in both cities. Yet, it was noticed that some isolated extreme temperature events gave rise to extreme ozone events in the studied area.

In 2015, the heat wave recorded in Casablanca was accompanied with an extreme ozone event that started the first day of the hot event.

In 2016, no heat waves were observed in Marrakech and no ozone events in Casablanca.

The comparison between the 90th percentiles calculated for all ozone data series and the thresholds stated by the national ambient air quality standards shows that the alert threshold (260 μg m^{-3} for hourly averages) wasn't exceeded in any station meanwhile the information threshold (200 μg m^{-3} for hourly averages) was exceeded in the station of Zrektouni in Casablanca.

Finally, it is noticed that during the study period, 33% of heat waves recorded in the coastal city of Casablanca were accompanied by extreme Ozone (O3) episodes, meanwhile, 70% of heat waves observed in the inland city of Marrakech were accompanied by extreme Ozone (O3) episodes, this may raise the question about the role the humidity may play in such cooccurrence.

The present work didn't reveal any accentuated tendencies for temperature and ozone extreme averages and events, however it showed that there is homogeneity in the found trends of these parameters and that the evolution of extreme events may be partly explained by the evolution of averages. The years 2012 and 2014 that recorded, respectively, the highest and the lowest maximum temperature, recorded also the highest and the lowest frequency of hot events. The absence of statistical significant tendencies in time series may be due to the shortness of the period used for this study, the 7 years period, allowed by the data available, mainly from ozone (O3) measurements, remains short and may not reflect the average and extreme temperature variability. In fact, some studies interested in extreme temperature over Morocco were performed on more than at least 20 years and have shown a general tendency toward hotter conditions[15,19,30].

Also, a similarity was noticed in the behavior of ozone (O3) time series from the stations of Jamaa Lafna and Zrektouni on one hand and Lmhamid and Ain Sebaa on the other hand, mainly regarding trends signs; this may be due to the similarity in their location characteristics: both Jamaa Lafna and Zrektouni are located in the center of the cities and are directly impacted by traffic pollution, meanwhile Lmhamid and Ain Sebaa are located respectively near to the airport of Marrakech and the industrial area of Casablanca, this makes them under the influence of industry and aviation origin pollutants.

The study of extreme events showed that the occurrence of heat waves increases the probability of appearance of extreme ozone events according to the degree of available humidity, this may justify a link between this events occurrence and a summer specific shared atmospheric large-scale pattern over Morocco. In fact, it has been shown that the occurrence of warm season hot events is directly related to large-scale atmospheric pattern that reaches the country from the north or the north-east. It appears mainly when the axis of the zonal ridge is located in the north of Morocco; the country is then under an eastern or north-eastern regime called Chergui that brings dry and warm air and may cause extreme hot and ozone events[15].

The current paper was interested principally in heat waves (more than three hot days) and their co-occurrence with extreme ozone events, none the less, some ozone events were observed after isolated hot temperature events (one or two hot days), this confirms the sensitivity of extreme ozone occurrence to recorded high temperature. In return, some extreme ozone events were observed without being trigged by extreme temperature, this may be due to the used approach for selecting hot events, in fact, the used statistical approach based on percentile thresholds may not consider some hot days that recorded temperatures below the percentile threshold and that would possibly have matched favorable conditions for photochemical air pollution.

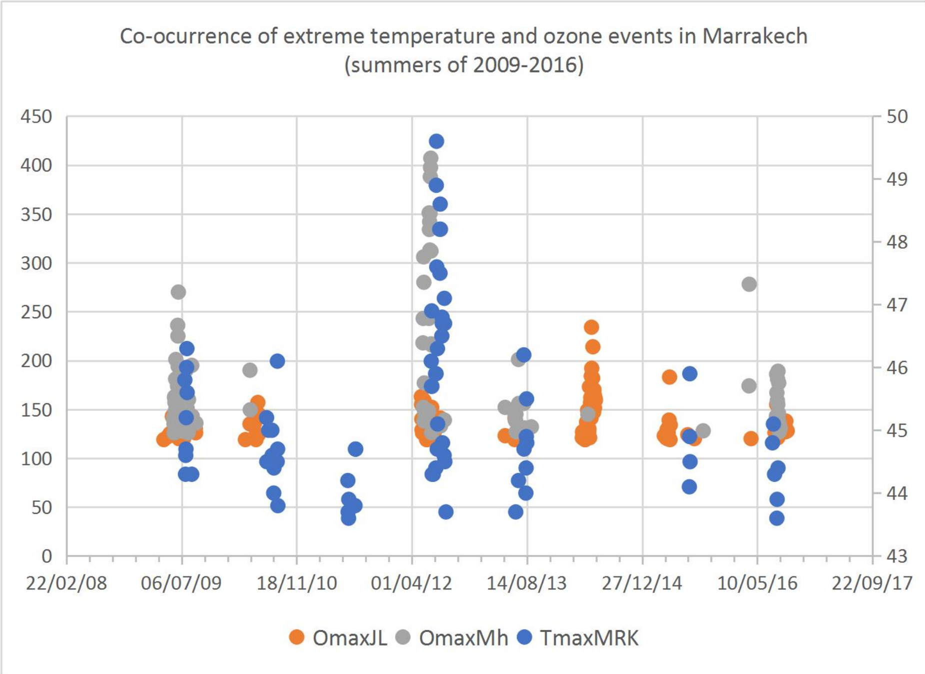

Figure 5. Scatterplot of summer temperature and ozone extremes in Marrakech between 2009 and 2016 (OmaxJL: extreme ozone events in Jamaa Lafna, OmaxMh: extreme ozone events in Lmhamid, TmaxMRK: extreme ozone events in Marrakech)

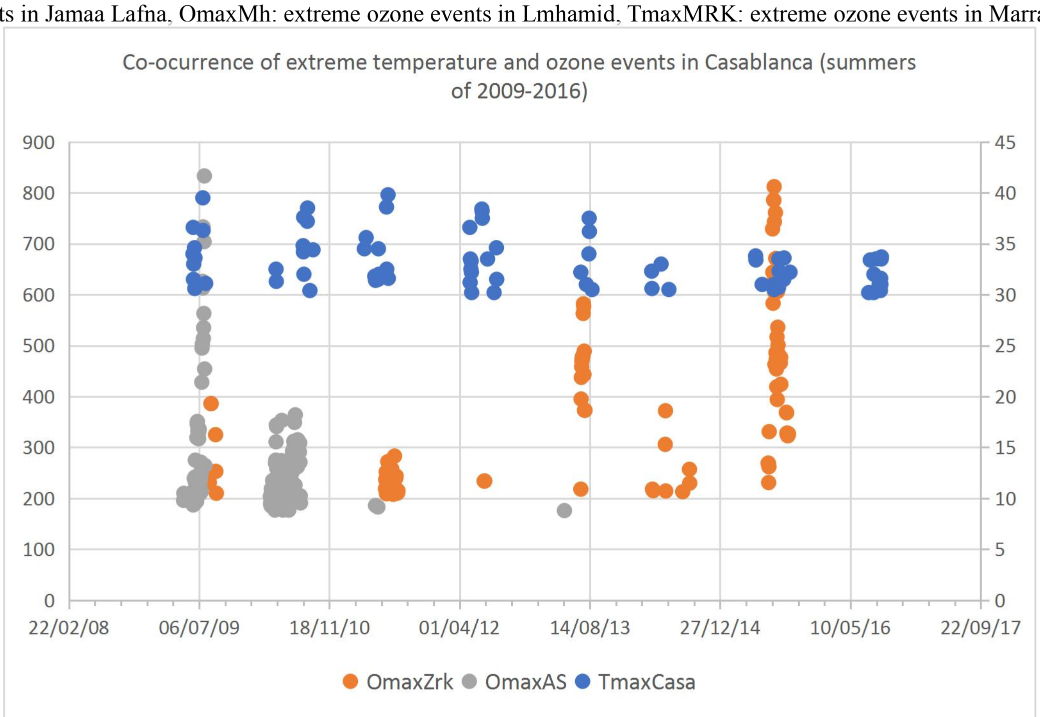

Figure 6. Scatterplot of summer temperature and ozone extremes in Casablanca between 2009 and 2016 (OmaxZrk: extreme ozone events in Zrektouni, OmaxAS: extreme ozone events in AinSebaa, TmaxCasa: extreme temperature events in Casablanca)

4. Conclusions

Although previous studies have examined individual behavior of climate change or ozone (O3) pollution in the cities of Casablanca and Marrakech, this study has made the first attempt to study the possible relationship between the recorded extremes in these parameters.

By combining 7 years site measurements of temperature and surface ozone (O3), we have assessed the extreme temperature and ozone trends and occurrence over two large populated cities from Morocco: the coastal city of Casablanca and the inland city of Marrakech.

Our study didn't reveal any accentuated tendencies for temperature and ozone extreme averages and events, however it showed that there is homogeneity in the found trends of these parameters and that the evolution of extreme events may be partly explained by the evolution in averages. Also, it showed that these two extremes are often coinciding or appearing slightly offset in time and that heat waves and humidity may impact the probability of appearance of extreme ozone events. However, it doesn't support the simple mechanistic argument stipulating that warmer temperatures make ozone pollution more severe, because ozone events may precede temperature events for some observed cases.

Moreover, and as meteorology is known to drive the occurrence of both extremes, our findings may justify the link between these events occurrences and a summer specific shared atmospheric large-scale pattern over Morocco. Further studies about this particular aspect will be our next step.

The present study may also be a first step with the hypothesis that ozone accentuates health vulnerability to short term at high temperature and that its effects are impacted by humidity, if other studies about the possible combined effects of temperature, humidity and ozone on human health are conducted. We also recognize the need to evaluate other rising pollutants that may significantly increase the impact of extreme temperature, mainly the Particulate Matter (PM) and Nitrogen Oxides (NOx). Results from like further studies could possibly be used to make recommendations during the high levels of temperatures and would help to develop reasonable policies for coping with heat waves.

Author Contributions

K.K. and H.N conceived, designed and wrote this paper. K.K. collected temperature data. H.N. collected ozone data. H.N. calculated and analysed trends in average extreme temperature and ozone. K.K. calculated extreme temperature and ozone events and heat waves and analyzed their trends and cooccurrence. Z.S. supervised the whole work of the two authors.

Conflict of Interest

No conflict of interest was reported by the authors.

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