

Article

Indirect Footprint of the 8 September 2023 Al Haouz (Morocco) Earthquake on Air Quality in Distant Cities

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Abstract

The Al Haouz earthquake (8 September 2023, Morocco) caused severe ground damage and initiated widespread human behavioural responses, raising concerns about possible indirect impacts on urban air quality. This study investigates the long-distance air quality response of near-surface particulate matter (PM₁₀, PM_{2.5}, and PM₁) and selected gaseous pollutants (NO₂ and CO), using high-time-resolution measurements from urban (Kenitra and Salé) and background (Maamoura) monitoring sites located hundreds of kilometres away from the epicentre. Baseline comparison, change-point detection, and correlation analyses consistently indicate the absence of an immediate response of PM levels at the exact arrival of the seismic waves, suggesting that direct mechanical effects of ground shaking were negligible at these sites. However, a multiday disruption of diurnal cycles was observed across all PM size fractions, causing up to an 111% increase in PM_{2.5} levels at the background station. These post-seismic changes are likely driven by intensified human mobility promoting traffic-related emissions propagating over local urban scales. The behaviour of gaseous pollutants further supports these findings: NO₂, a short-lived tracer of traffic activity, showed pronounced and repeated anomalies during the night and early morning following the earthquake, closely tracking changes in human mobility. CO, by contrast, displayed weaker and smoother variations, consistent with its longer atmospheric lifetime. Therefore, the responses of short-lived (NO₂) and longer-lived (CO) pollutants provide a diagnostic framework for unravelling rapid behavioural emissions changes from background atmospheric variability during extreme events. Together, these observations provide the first evidence that strong earthquakes can induce complex and multi-phase perturbations in air quality over regional scales, far from epicentres.

Keywords: Al Haouz earthquake; urban air quality; nitrogen dioxide; carbon monoxide; particulate matter; human-environment interactions; Morocco

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1. Introduction

Strong earthquakes ($M > 6$, where M indicates the Richter magnitude) occur in regions of accumulated tectonic stress, accompanied by gradual deformation of the Earth's crust [1,2]. Compounds (SO_2 , CO_2 , H_2S , CO , O_3 , and CH_4) and chemical elements (He, Ne, Ar, and Rn) may be released in anomalous amounts from active fault zones in the lead-up to, during, and following strong earthquakes [3–7].

Several case studies based on both ground-based and satellite observations have identified CO and SO_2 as potential atmospheric indicators of seismic activity or precursors thereof [3,4]. For instance, real-time air-quality measurements revealed SO_2 anomalies several hours before the 21 September 1999, Taiwan earthquake ($M = 7.3$) [3], while elevated SO_2 levels were also observed before a large earthquake ($M = 6.8$) on 31 March 2002, in eastern Taiwan. Similarly, CO anomalies were detected before, during, and after the 2008 Wenchuan earthquake ($M = 8.0$) and the 2013 Lushan earthquake ($M = 7.0$) using AIRS satellite observations [4].

Strong earthquakes may also be associated with the dispersion of large amounts of dust into the atmosphere. Okada et al. [8] found changes in atmospheric aerosol characteristics over the Arabian Sea following the 2001 Gujarat earthquake ($M = 7.7$). They reported a post-seismic increase in aerosol optical depth (AOD), originating from the earthquake preparation zone. By analysing backward air-mass trajectories, these changes were linked to dust released during widespread village destruction and then transported by strong winds. Qin et al. [9] similarly detected elevated AOD levels near active fault zones up to seven days before the 2008 Wenchuan earthquake, relating these anomalies to ionospheric instabilities and unusual atmospheric conditions. More recently, Ghosh et al. [1] documented increases in AOD attributed to dust generated in fault regions following the earthquake.

In urban environments, disturbance of large reservoirs of road deposited and crustal dust during earthquakes could result in their emission to the atmosphere and thus contribute to elevated particulate matter (PM) levels [10]. Previous studies have shown that vibration of dusty surfaces inevitably leads to the re-entrainment of particles into the atmosphere, with specific threshold conditions governing the onset of this resuspension under oscillatory motion [11]. Furthermore, seismic events are known to mobilise particulate matter through the generation of dust clouds and the release of particles from soils and roads during intense ground shaking, while the mechanical effects of seismic surface waves can propagate over large distances, producing near-surface disturbances and loosening of crustal materials [12].

Evidence from post-earthquake air quality observations, such as those following the February 2023 Kahramanmaraş earthquake, demonstrates very high respirable (30.8 mg/m^3) and total dust (33.7 mg/m^3) concentrations in the immediate aftermath of seismic events, indicating a substantial release of particulate matter into the atmosphere [13,14]. While previous studies have documented earthquake-related atmospheric anomalies in proximity to active faults [4,12] or at regional scales using satellite-derived indicators such as aerosol optical depth [8,9], evidence for long-range impacts on urban air quality remains extremely limited.

On the night of 8 September 2023, at approximately 11:11 pm local time, western Morocco was struck by a devastating earthquake. This seismic event, hereafter referred to as the Al Haouz earthquake, had a magnitude of $M = 6.8$ and occurred at relatively shallow depth, with its epicentre located in the High Atlas Mountains within Al Haouz province, where entire communities were almost destroyed [15] with almost 3000 casualties reported [16]. The seismic waves from the Al Haouz earthquake were felt well beyond the epicentre region, reaching several cities across Morocco, such as Kenitra, Rabat, Casablanca, Agadir, and Essaouira.

Alongside the physical impacts, human responses to the event raised additional concerns. Ottria et al. [17] reported that fear was the dominant emotion experienced by individuals exposed to the seismic shaking in Marrakech, and that this intense emotional response strongly influenced their decision-making, leading many people to engage in spontaneous evacuation rather than adherence to recommended protective actions. Previous studies have demonstrated that these emergency responses and abnormal mobility during disasters, including earthquakes, can considerably influence urban air pollution patterns [18].

The present study investigates whether a strong seismic event can be associated with short-term and measurable changes in concentrations of some key criteria pollutants in cities located several hundred kilometres from the earthquake epicentre. In this study, we examine the high-time-resolution response of ground-based PM, CO, and NO₂ levels in urban areas situated nearly 400 km away from the Al Haouz earthquake source region. To our knowledge, observational data linking urban air quality perturbations to seismic events remain limited. This work expands the available evidence by capturing short-term and multi-phase perturbations in air quality in distant cities following a strong earthquake.

2. Materials and Methods

2.1. Air Quality Measurements

Real-time high-time resolution observations of air quality metrics (PM₁, PM_{2.5}, PM₁₀, CO, and NO₂) associated with earthquake-related events were analysed from 1 to 30 September 2023. The measurement period was selected to capture both background conditions and the days surrounding the Al Haouz earthquake. Unless otherwise stated, analyses of CO and NO₂ were performed for the period 1–20 September 2023, corresponding to the immediate pre- and post-earthquake period, whereas the PM time series were extended until 30 October 2023 to characterise longer-term variability and to provide context for other atmospheric events. Nitrogen dioxide (NO₂) and carbon monoxide (CO) were recorded every 30-min, while particulate matter concentrations (PM₁₀, PM_{2.5}, and PM₁) were measured every two minutes. Gas-phase pollutants were measured at an urban location in Kenitra, while PM levels were analysed at an urban (Salé) and a background observation site (Maamoura) near the Rabat metropolitan region. Sampling locations, together with the epicentre site of the Al Haouz earthquake, are shown in Figure 1, while their characteristics, including site classification, geographical coordinates, measured pollutants, and sampling time resolution, are summarized in Table S1.

NO₂ concentrations were measured using a chemiluminescence analyser (Horiba, APNA-370, Kyoto, Japan), operating at a flow rate of 0.8 L/min, with a minimum detection limit of 0.5 ppb for concentrations below 0.2 ppm. CO was monitored using a non-dispersive infrared (NDIR) technique with an automatic analyser (HORIBA, APMA-370, Kyoto, Japan), at a flow rate of 1.5 L/min and a minimum detection limit of 0.05 ppm for concentrations below 10 ppm [19,20]. The performance features of the gaseous pollutant measurements followed national standards, namely NM EN 14626:2012 for CO [21] and NM EN 14211:2012 for NO₂ [22].

High (2-min) time resolution data of three PM fractions (PM₁₀, PM_{2.5}, and PM₁) were obtained using PurpleAir sensors (<https://www.purpleair.com/>) from the Rabat suburban scale air quality network operated by the MAGIC project [23]. The PurpleAir monitor is a low-cost sensor that uses integrated Plantower PMS5003 optical particle counters (Plantower Technology, Nanchang City, Jiangxi Province, China). It operates on the laser light scattering principle: a fan draws air past a laser beam, and light scattered by individual particles is detected to infer particle count and size via a proprietary algorithm. The sensor reports particle number concentrations in six size bins (>0.3, >0.5, >1.0, >2.5, >5.0, >10 µm) and derives mass concentration estimates for PM₁, PM_{2.5}, and PM₁₀. Manufacturer-stated counting efficiency is 50% at 0.3 µm and 98% at ≥0.5 µm, with an effective PM_{2.5} range of

0–500 $\mu\text{g}/\text{m}^3$ and a maximum consistency error of $\pm 10 \mu\text{g}/\text{m}^3$ (0–100 $\mu\text{g}/\text{m}^3$) or $\pm 10\%$ (100–500 $\mu\text{g}/\text{m}^3$). Evaluations show the sensor can overestimate regulatory $\text{PM}_{2.5}$ under certain ambient conditions and that its PM_{10} channel is relatively unresponsive to coarse-mode dust due to optical geometry and inlet limitations [24].

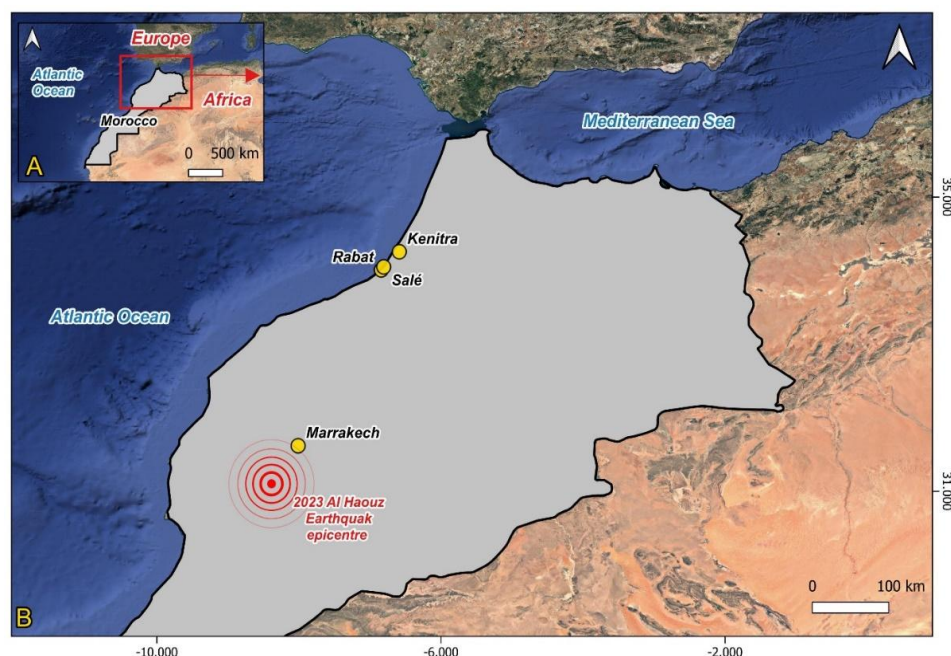


Figure 1. (A) Inset map showing Morocco's position at the intersection of Africa and Europe. (B) Locations of the air quality monitoring sites (yellow circles) in relation to the Al Haouz earthquake epicentre (red circles).

2.2. Time Series Analysis and EDA of the Air Quality Data

Concentration time series of the gas phase pollutants were simply visualised at their original resolution, and the effects of the earthquake were analysed qualitatively. PM concentration time series underwent in-depth statistical analysis. Outliers were removed prior to analysis using a two-step filtering method that ensures that only real outliers (i.e., isolated values) are removed while real extreme values that persist over a longer sampling period are kept. The first step is standard isolation forest outlier detection [25], which is followed by a temporal filter, develop in-house for the Purple Air data collected in our measurement campaign, that operates on the outliers identified by the isolation forest and removes them only if they persist for less than 30 min and similar extreme values are found in less than 10 neighbouring data points. This approach resulted in the exclusion of less than 1% of the dataset. The quality-controlled time series were then aggregated into hourly averages, used to identify diurnal variations.

To compare the post-seismic response to typical diurnal patterns, a baseline was constructed by regrouping data retrieved during the same hour of the day from September, excluding the day of the earthquake and the two following days. Box plots were then generated for every hour, and limits of typical behaviour were established based on the interquartile range of this distribution. Diurnal periodicity was retrieved from the hourly mean levels. Post-seismic perturbations were identified as either concentrations that are superior to the 75th percentile or as temporal patterns that do not follow the diurnal cycle defined by the mean concentrations.

To assess the immediate effect of seismic events on PM concentrations, expected peak ground acceleration values were calculated using Ground Motion Prediction Equation (GMPE) modelling and were compared to the threshold levels needed for observable soil

resuspension [26]. Multiple statistical tests, including targeted change-point analysis was performed focusing on the period following the event [27]. Three complementary statistical methods were applied to identify abrupt and unexpected shifts in the PM time series. These methods allowed for precise temporal identification of co-seismic PM changes, while minimising confounding effects from diurnal variations. We used the Pruned Exact Linear Time (PELT) algorithm to detect multiple change-points in the mean and variance [28,29]. The PELT algorithm was implemented using the modified Bayesian Information Criterion (BIC) penalty, which automatically balances model fit and complexity while reducing the risk of over-detecting spurious change points [30]. A CUSUM-based approach assuming at most one change (AMOC) was then applied to identify the most significant mean shift [31], and the non-parametric Pettitt test was used to detect median shift without assuming normality. Furthermore, multi-scale impact analyses were performed by comparing the distribution and percentage differences in pre- and post-seismic concentrations at timescales ranging from 1 h to 1 week.

2.3. Seismic Activity Description

To characterise ground movement associated with the 8 September 2023 Al Haouz earthquake and examine its potential link with short-term air quality variability, seismic recordings from the RTC (Rabat, Morocco) station (<https://terremoti.ingv.it/instruments/station/RTC>, accessed on 27 February 2026) were analysed. This station is part of the Mediterranean Very Broadband Seismographic Network (MedNet), managed by the National Institute of Geophysics of Morocco (INGM). Three high-gain broadband channels, HHE (East–West), HHN (North–South), and HHZ (Vertical), were retrieved in ASCII format, covering the period from 9:00 to 11:59 pm UTC on 8 September 2023 (local time: 10:00 pm on 8 September to 12:59 am on 9 September). A continuous seismogram was first reconstructed to identify the temporal arrival and duration of the earthquake signal within the record (Figures S1 and S2 in Supplementary Materials). To synchronise seismic activity with atmospheric observations, the seismic signal (recorded at very high frequency, 0.01 s) was harmonised with the PM dataset (2-min resolution). Ground-motion intensity within each PM sampling interval was quantified using the Root Mean Square (RMS) amplitude of the seismic velocity signal. The use of RMS amplitude as a proxy for vibrational energy is a well-established standard in seismology, as it effectively smooths high-frequency noise while capturing the integrated energy of the seismic wave train [32].

Statistical associations between seismic energy and PM concentrations were assessed using Spearman's rank correlation. In addition, lagged correlation analysis was conducted by progressively shifting the PM time series relative to the seismic RMS signal to explore possible delayed PM responses [20,33]. All statistical analyses were conducted using R version 4.5.2 [34].

3. Results and Discussion

3.1. Gas Phase Pollutants (CO and NO₂)

3.1.1. General Description

Figure 2 presents complementary perspectives on the temporal variability of carbon monoxide (CO) and nitrogen dioxide (NO₂) concentrations measured from 1 to 20 September 2023, including a period of seismic event of 8 September 2023. NO₂ in urban environments is primarily a by-product of high-temperature combustion in internal combustion engines, while CO serves as a tracer for incomplete combustion and, in some cases, may also reflect crustal degassing processes. Across the full period, both CO and NO₂ exhibit well-defined and recurrent diurnal cycles, typical of urban emissions dominated

by road traffic. Concentrations generally peak during morning and evening hours, coinciding with commuting periods, and decrease during late-night/early-morning hours when activity levels are lowest. Many studies reported that this bimodal pattern of NO_2 is mainly due to the increase in the emission rate from traffic at the start and end of the day, coupled with boundary layer height changes in the early morning and into the evening [35,36]. CO follows a pattern similar to NO_2 but with smoother and less pronounced peaks, consistent with its longer atmospheric lifetime and broader emission profile (including incomplete combustion from vehicles and other sources) [37]. In contrast, NO_2 displays stronger short-term variability, reflecting its short atmospheric lifetime of several hours in the boundary layer during daytime [38] and sensitivity to immediate combustion emissions [39,40].

The near-synchronised peaks for both pollutants support the conclusion that vehicular emissions are a major driver of their concentrations in the study area [41]. A noticeable weekend reduction is observed for NO_2 compared with CO, consistent with their chemical behaviours: NO_2 responds more directly to short-term changes in fresh emissions, whereas CO exhibits more temporal inertia. The amplitude of variability may reflect the combined influence of emission variability and boundary-layer dynamics, especially during nighttime and early morning when mixing heights are low. Meteorological effects are also likely responsible for the slight day-to-day fluctuations observed within each pollutant. Rozante et al. [42] discussed that the weekly and diurnal cycle of CO concentration in urban areas is directly related to meteorological conditions and emission patterns.

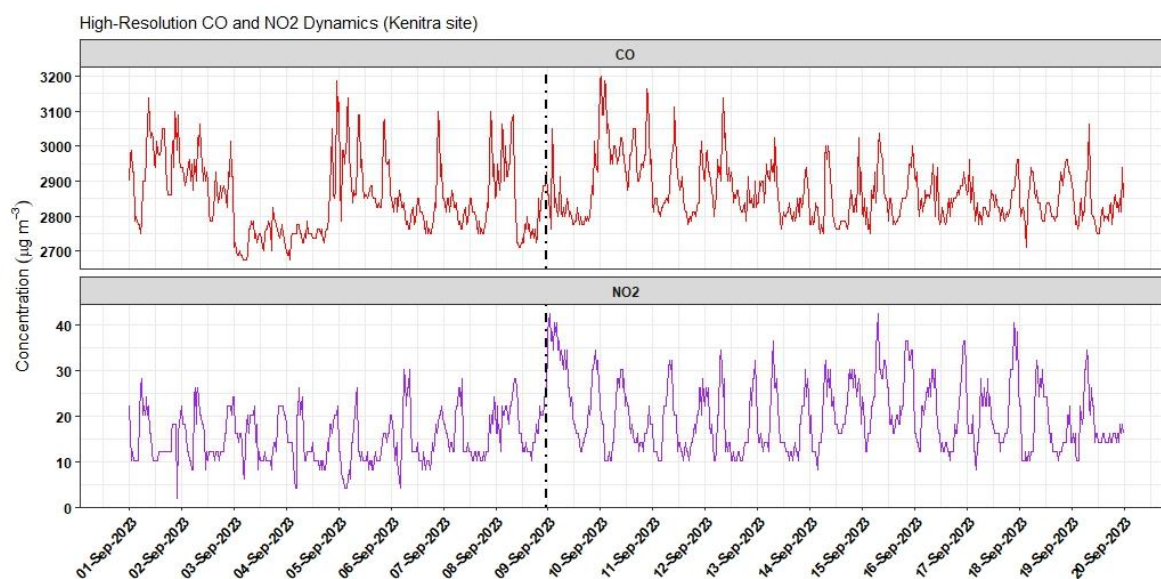


Figure 2. Hourly concentrations of carbon monoxide (CO) and nitrogen dioxide (NO_2) measured from 1 to 20 September 2023. The vertical black dash-dotted line denotes the occurrence of the Al Haouz earthquake on 8 September. Data shows the transition from pre-seismic background levels to earthquake-influenced atmospheric dynamics.

3.1.2. Short-Term Dynamics of Urban NO_2 and CO Concentrations

Figure 3 illustrates the hourly concentrations of NO_2 and CO measured around the 8 September 2023 seismic event. The NO_2 concentrations are characterised by strong diurnal fluctuations and pronounced weekday peaks, reaching approximately $40 \mu\text{g}/\text{m}^3$, while the CO concentrations follow a daily cycle but with broader peaks, in line with its longer atmospheric lifetime and more diffuse emission sources. The period of measurement includes the occurrence of a major earthquake on Friday, 8 September 2023, at 11:11 pm local time. Although the monitoring site at Kenitra city is geographically distant from the

earthquake epicentre, the time series shows noticeable deviations from baseline behaviour around the time of the earthquake. The measured concentrations reveal transient but measurable changes in urban NO₂ and CO levels in the hours following the seismic event. These variations are most evident in NO₂, which is closely tied to short-lived combustion sources such as road traffic [38]. Furthermore, Lamsal et al. [43] demonstrate strong coupling between NO₂ concentrations and short-term emission changes. Beginning late on 8 September and continuing into 9 September, these changes are unlikely to result from direct geophysical effects, while they likely reflect indirect consequences related to enhanced nighttime mobility following the earthquake. Guo et al. [44] show distinct temporal peaks in population movement following major earthquakes. The NO₂ profile provides the clearest evidence of the socio-behavioural response to the seismic event, owing to its short atmospheric lifetime and strong coupling to traffic-related emissions, which makes it highly sensitive to immediate changes in human activity [38,39,45]. Further studies confirm NO₂ responds more strongly than other pollutants to behavioural changes [46,47]. Those changes were brief, and emissions returned to typical patterns within 1–2 days. Likewise, CO concentrations exhibit irregular fluctuations superimposed on their usual traffic-related variability. CO remains within its expected concentration range but shows slightly elevated early-morning peaks on 9–10 September compared with earlier weekdays. Sheel et al. [48] highlighted that CO's longer atmospheric lifetime of a few months makes it less sensitive to unexpected changes in human behaviour. However, the subtle variability increase likely reflects fluctuations in traffic flow and altered nighttime mobility during the seismic event. While the urban anthropogenic signal is dominant, we cannot entirely rule out seismic degassing. Studies on the so-called gas hammer effect indicate that seismic wave propagation can mechanically perturb shallow soil gas reservoirs, promoting the upward migration of crustal gases (such as CO, CO₂, CH₄, H₂, and Rn) into the atmospheric boundary layer [49,50]. That gas emissions may occur even at distances of several hundred kilometres from the epicentre, depending on ground acceleration and subsurface permeability [50]. While highly speculative in an urban context, minor releases from porous soils of the coastal plain cannot be entirely excluded.

The most striking feature of the post-seismic period is the emergence of three distinct pulses in NO₂ concentrations between 12:00 am (midnight) and 09:00 am on 9 September, as shown in Figure 4. This triple-peak morphology represents a significant departure from the standard diurnal cycle observed in the first week of September. Wang et al. [51] have documented multi-phase mobility increases (initial displacement, relocation, return) after a natural disaster. The first peak (~01:00–02:00 am) is likely related to the evacuation phase. This peak aligns with the immediate mass movement of residents from indoor environments. The rush in NO₂ is a direct proxy for the sudden eruption of many internal combustion engines as citizens sought safety in open spaces or utilised vehicles as mobile shelters. The instability phase started around 04:00–05:00 am. This secondary peak likely reflects the impact of aftershocks, which sustained a state of public alarm. This phase is characterised by localised traffic movements as residents relocated between safe zones or travelled to check on relatives, preventing the typical nighttime washout of pollutants. The final peak may represent the re-occupancy/return wave ongoing around 07:00–08:00 am. As suggested by the time series, this final peak represents the home-return wave. With the onset of daylight and a perceived reduction in immediate danger, a large-scale movement of the population back to residential quarters occurred. This phase coincided with the onset of the standard morning rush hour, leading to the combined effects of post-earthquake human mobility and routine traffic emissions, which resulted in the highest NO₂ concentrations recorded during the entire 20-day study period, as discussed earlier in Figure 2. An important limitation of this study is the absence of independent mobility datasets, such as traffic counts or anonymized mobile phone records. Consequently, while

the observed air-quality changes are temporally consistent with increased human mobility following the earthquake, the proposed mechanism remains a hypothesis supported by circumstantial evidence rather than direct observational confirmation.

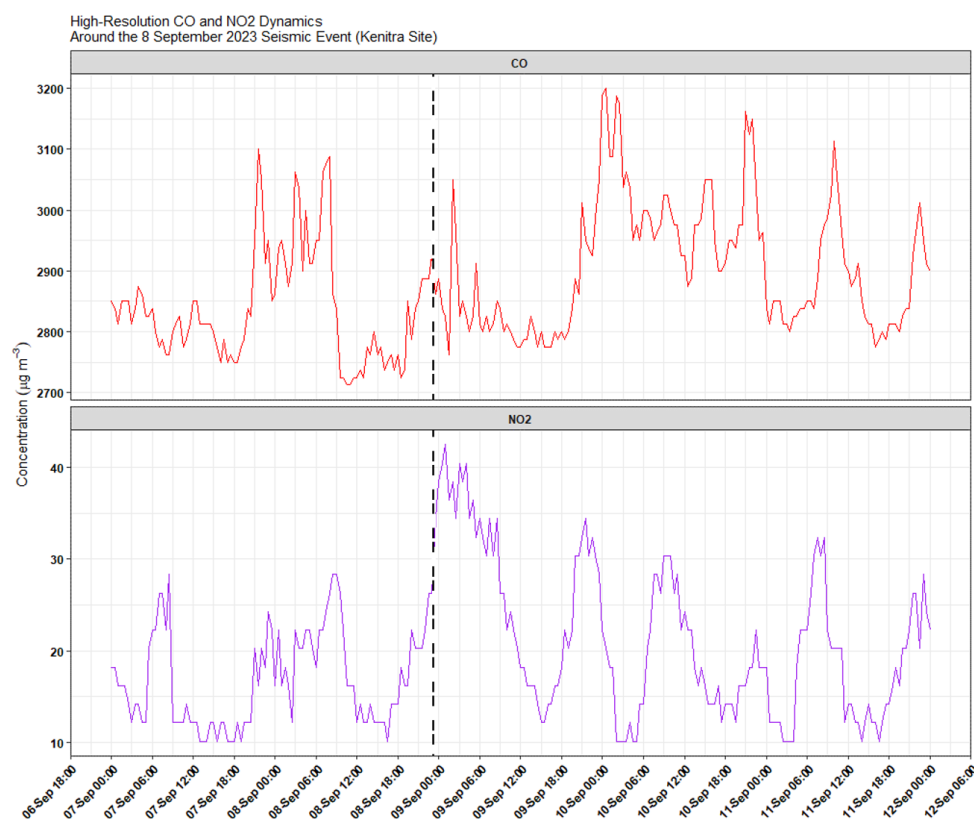


Figure 3. Hourly concentrations of NO_2 and CO measured between 7 and 12 September 2023. The 8 September earthquake event is indicated by the vertical black dash-dotted line illustrating the temporal transition between pre-seismic baseline levels and post-seismic atmospheric anomalies for CO and NO_2 .

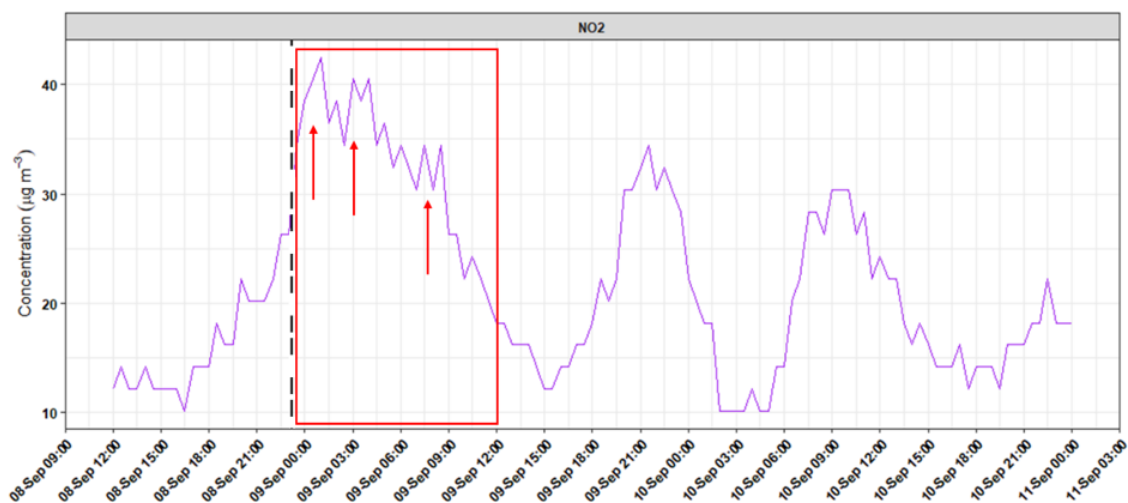


Figure 4. Hourly NO_2 concentrations in urban Kenitra during the 2023 Al Haouz earthquake. The red box and arrows identify a triplet of peaks observed in the immediate post-seismic window between midnight and 09:00 am on 9 September. These signatures represent a marked departure from the typical nocturnal baseline and highlight the immediate short-term atmospheric impact of the seismic event. The vertical black dash-dotted line denotes the occurrence of the Al Haouz earthquake on 8 September.

3.2. Particulate Matter

Concentration Time Series at the Two Monitoring Sites

Figures 5 and 6 show raw (2-min) and hourly concentrations of PM_{10} , $PM_{2.5}$, and PM_{10} at the urban (Salé, Figure 5) and the background site (Maamoura, Figure 6) from 1 September to 30 October 2023. Figures S3 and S4 show the ratios and differences between mass concentrations of different size fractions. Values of the ratio superior to 0.5 indicate the dominance of the smaller fraction, with more than 50% of the total PM mass loading contributed by the fine particle fraction. The difference plots quantify coarse particle concentrations. We acknowledge that Purple Air sensors tend to overestimate PM levels especially at high humidity locations, and present humidity corrected data for comparison in Figure S5. Humidity corrected time series are less affected by single-point extreme peaks but do preserve the overall temporal profiles and sustained high or low values in general, therefore using the raw data does not impact the qualitative analysis presented below.

Both sites exhibit pronounced diurnal cycles of PM levels in all size fractions, pointing to a highly dynamic aerosol environment at the sampling locations. The difference and ratio plots describing the relative propensity of the different size fractions show that, in general, smaller fractions, $PM_{2.5}$ and PM_{10} , contribute the majority of the PM mass loadings at both sites. This indicates that PM levels are mainly determined by local anthropogenic emissions that yield a large amount of fine particles, such as transport and other combustion-related activities. The high-amplitude short-scale variability (from 0 to 1) of the fine-to-coarse particle ratios (Figures S3 and S4) indicates intermittent activity of large particle sources, which can potentially be attributed to marine emissions, combined with a wind direction favouring transport towards the sampling sites [52–54]. This latter is further corroborated by the fact that the fluctuation amplitude changes at both sites in a concerted manner. Detailed analysis of this behaviour, however, is beyond the scope of this study. To further assess potential meteorological influences, ERA5-Land reanalysis fields corresponding to the principal air-quality perturbation phases are presented in Figure S6. The corresponding processed meteorological datasets, including temperature, relative humidity, planetary boundary layer height, and wind gust velocity during the pre- and post-seismic period of the 8 September 2023 Al Haouz earthquake, have been made publicly available through a Zenodo repository [55]. These fields do not reveal unusual synoptic-scale meteorological conditions that could account for the observed pollutant anomalies.

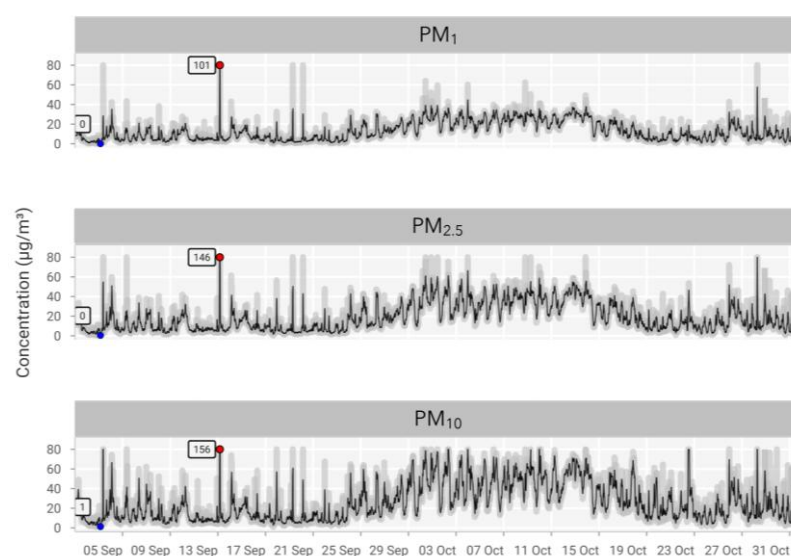


Figure 5. PM_{10} , $PM_{2.5}$, and PM_{10} mass concentration time series from 1 September to 31 October 2023, at the urban observation site (Salé). The shaded areas represent raw data at the original two-minute

resolution after outlier removal. The continuous black line shows hourly mean concentrations derived from the cleaned raw data. The blue and the red dots represent, respectively, the minimum and the maximum hourly mean concentrations observed during the study period.

The overall patterns of the time series are similar at both sites, but there are pronounced differences between the urban and background locations. Typical PM levels are higher in Salé, and important short-term changes, particularly for PM_{10} and $PM_{2.5}$, suggest a greater influence of local sources such as traffic, resuspension, and nearby anthropogenic activities. In contrast, the background site is characterised by lower baseline levels and smoother temporal profiles with fewer extremes, indicative of a more diluted pollution environment and lower intensity of anthropogenic sources, attributed to the much smaller population density near the sampling site.

While pronounced diurnal cycles characterise the time series during the whole sampling period, a departure from the typically low baseline is superimposed on them for an approximately three-week-long period between 24 September and 16 October. During this period, PM_1 and $PM_{2.5}$ concentrations are close to equal at the urban and the background site, which suggests that the same regional source contributes to the fine particle fraction during this period. Only the coarse fraction (Figures S3 and S4) concentrations exhibit considerable differences. The fine-to-coarse ratios over this period are around 0.8, and the amplitude of the short-scale fluctuations is reduced to about 0.2, showing the dominance of the regional fine aerosol source likely from combustion-related and secondary anthropogenic sources [56,57].

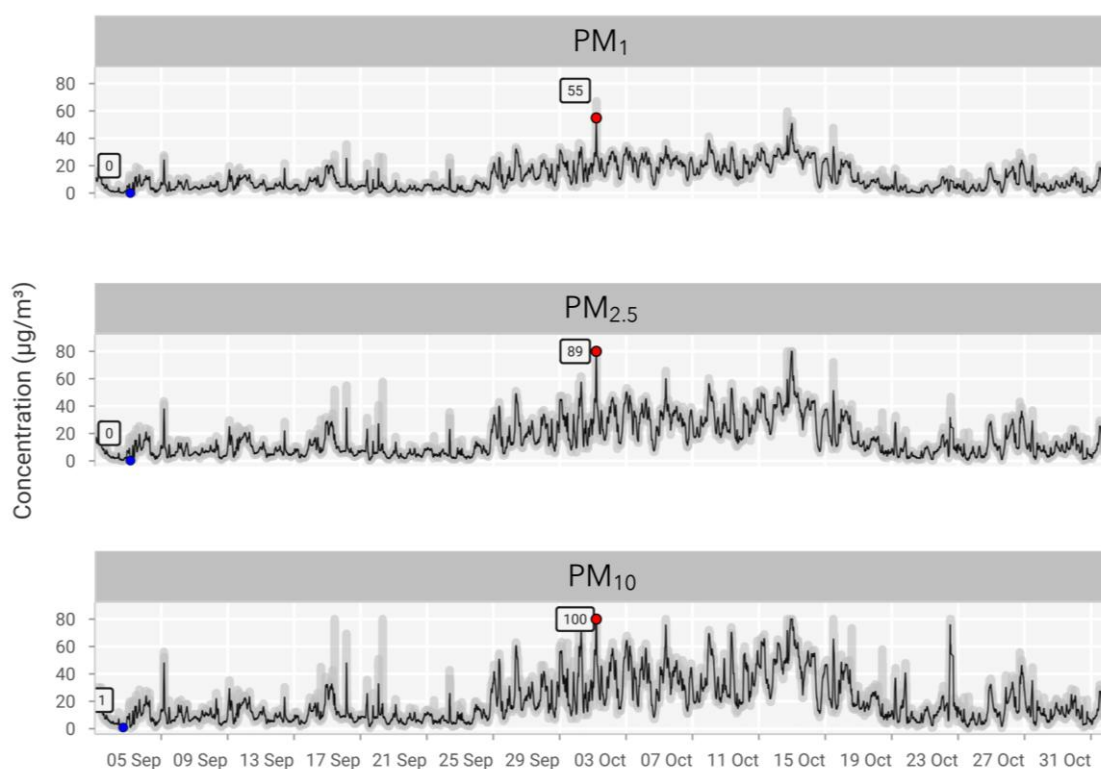


Figure 6. PM_1 , $PM_{2.5}$, and PM_{10} mass concentration time series from 1 September to 31 October 2023, at the background observation site (Maamoura). The shaded areas represent raw data at the original two-minute resolution after outlier removal. The continuous black line shows hourly mean concentrations derived from the cleaned raw data. The blue and the red dots represent the minimum and the maximum hourly mean concentrations observed during the study period.

Interestingly, the effects of Storm Bernard and its precursor event (19 and 22 October 2023), which caused reduced visibility and an orange sky in the Rabat region, show up as elevated baseline concentrations in the coarse particle time series and as the temporary dominance of the coarse aerosol fraction from 19 to 23 October, at both sampling locations. However, the event appears to produce only one extreme peak in PM₁₀ levels on 22 October at the background site. At the urban site, the impact of the dust event remains basically indistinguishable from the diurnal variability. Because this meteorological event occurred more than one month after the Al Haouz earthquake, it is independent of the post-seismic period investigated in this study and is discussed here solely to illustrate the response of the PM measurements to a well-defined regional aerosol event.

In summary, the Rabat metropolitan area represents a highly dynamic environment with influences from a large number of local and regional sources, which makes even the detection of major events, like Storm Bernard, difficult from our optical PM measurements. Identifying subtle changes in PM levels induced by the distant earthquake requires high-level statistical and time series analysis, which is introduced in the following sections.

3.3. PM Response to the Seismic Activity

Impact analysis comparing the distributions of PM_{2.5} concentrations observed for 1 h, 1, 2, and 7 days before and after the earthquake was performed for both sites. Boxplots showing the differences in the distributions for the above three time-ranges before and after the seismic event are shown in Figure 7 (Urban site, Salé) and Figure 8 (Background site, Maamoura).

Looking at the boxplots, a clear pattern emerges showing only minor changes in the vicinity of the event, with the urban site even exhibiting reduced PM_{2.5} levels in the hour after the earthquake compared to the previous hour. The maximal percentage change (111% for the background and 77% for the urban site) is observed the day after the earthquake. The impact starts to diminish from the second day on, but is still significant, especially for the background site where the two-day averages before and after still show 97% percent of difference. The comparison of the 1-week-long periods shows that the enhancement in the observed PM levels decays over one week for both sampling locations, but remains more significant at the urban site, which otherwise exhibits smoother concentration profiles, less pronounced diurnal cycles, lower typical concentrations, and fewer extreme values than the urban site. Other size fractions exhibit very similar patterns (Figures S7 and S8).

This overview suggests that immediate impacts of the earthquake are imperceptible or inexistent, while long-term response—potentially linked to human reactions to the earthquake—produces significant perturbations in the PM levels for multiple days after the event. In the following sections, we explain the lack of immediate impacts and corroborate it with statistical analysis. Then we provide a detailed analysis of the long-term response, identifying temporal profiles and linking them to potential sources.

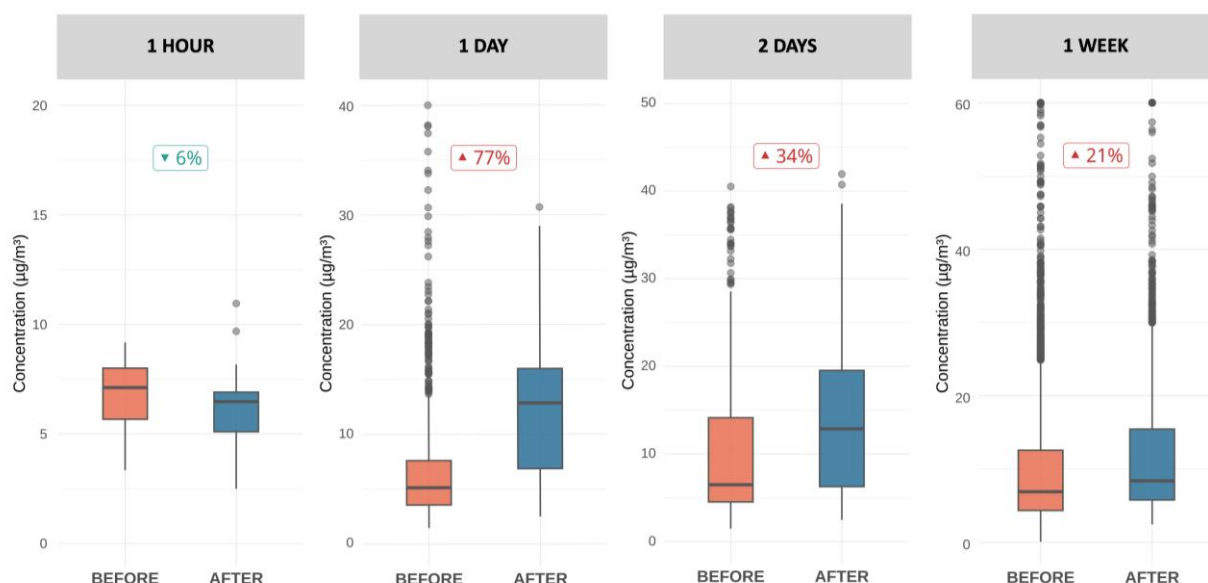


Figure 7. Boxplots comparing the distributions of observed hourly mean, cleaned $PM_{2.5}$ mass concentrations at the urban site, aggregated over different periods of time (1-h, 1-day, 2-day, and 1-week) before and after the earthquake. The annotation indicates the percentage change of the mean values together with their direction. The percentages and arrows in the insets indicate the percentage change before and after the earthquake, the arrows indicate the direction of the change. Further, increase is highlighted in red and decrease in green colour.

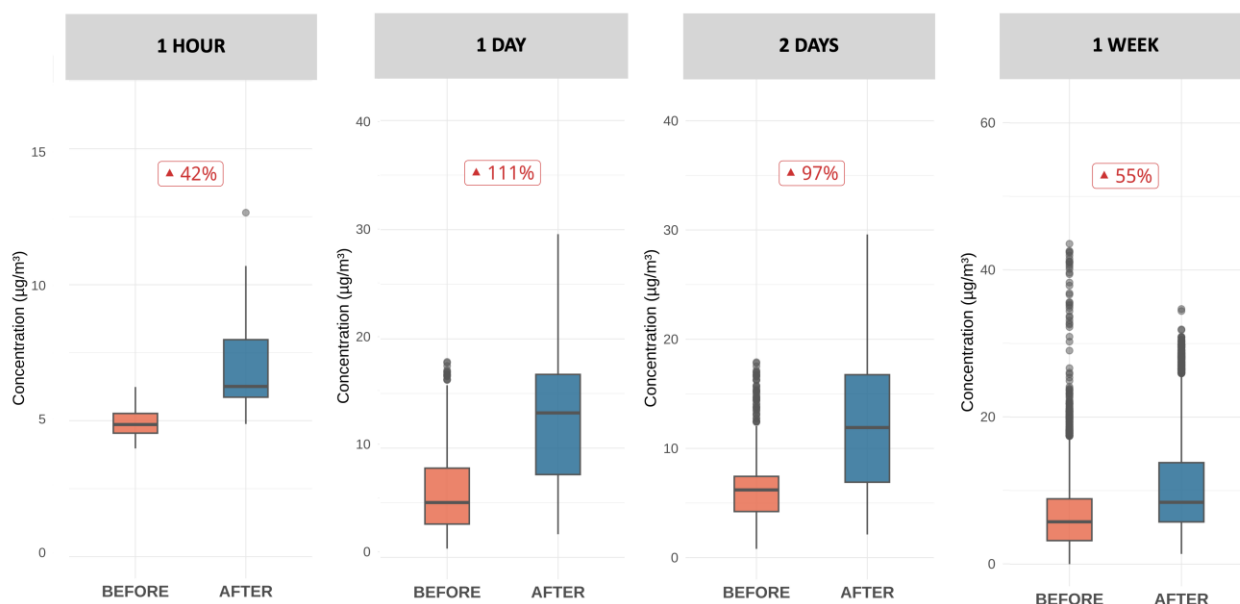


Figure 8. Boxplots comparing the distributions of observed hourly mean, cleaned $PM_{2.5}$ mass concentrations at the background site, aggregated over different periods of time (1-h, 1-day, 2-day, and 1-week) before and after the earthquake. The annotation indicates the percentage change in the mean values together with their direction. The percentages and arrows in the insets indicate the percentage change before and after the earthquake, the arrows indicate the direction of the change. Further, increase is highlighted in red colour.

3.3.1. Immediate Impact

An immediate impact on PM levels could be due to resuspension of fine particles from the soil due to the vibrations. An immediate increase—like what has been observed at the Maamoura site—in the PM concentrations a few minutes after the earthquake would in itself suggest that this is a viable pathway to perturb ground-level aerosol concentrations. We have performed simplified model calculations to estimate the shaking energy, assuming a uniform rocky and sandy soil. We assessed the potential for seismically induced resuspension of fine particles (PM_{2.5} and PM₁) by modelling the ground shaking at a distance of 400 km from a magnitude 6.8 earthquake. Peak ground acceleration (PGA) on bedrock was estimated using a general log-linear attenuation model for shallow crustal earthquakes, yielding a bedrock PGA of approximately 0.006 g. To account for local site effects, we applied amplification factors that are typical for engineering practice: a low factor of 1.5 for a uniform stiff rocky soil profile and a higher factor (3.5) for a hypothetical uniform sandy soil profile [58]. The resulting surface PGA values were found to be 0.01 g and 0.03 g for the rocky and the sandy soil profile, respectively. These levels of ground motion are very low or even imperceptible, and remain several orders of magnitude below the acceleration threshold (0.1 g) [59] required to directly dislodge and suspend fine particles from a soil surface. Therefore, an immediate physical response of soil resuspension to ground shaking is not plausible. The results of these model calculations are further supported by the large spread and inconclusive values of multiple correlation coefficients and lagged correlations between the seismic activity and the PM concentrations, using multiple proxies such as the vertical, Eastern, and Northern components of the amplitude or RMS energy envelope. Spearman's rank correlation between seismic intensity and instantaneous PM concentrations yielded non-significant results ($p > 0.15$), with no statistically distinct change-point detected at the earthquake occurrence time across PELT, AMOC, and Pettitt analyses.

3.3.2. Medium-Term Anthropogenic Impacts

Figures 9 and 10 present the high-temporal-resolution PM₁₀, PM_{2.5}, and PM₁ levels at the urban and the background site, respectively, for 8, 9, and 10 September. It is compared to a reference baseline, constructed as described in the methods section, representing typical diurnal patterns that reflect regular atmospheric processes and emissions cycles and are widely used to define normal behaviour in air quality studies [45,60]. When hourly values remain within the interquartile range (IQR) of the boxplots, they can be considered representative of normal variability. Values exceeding the upper quartile indicate atypical conditions and may reflect unusual emission sources or atmospheric processes [61].

In accordance with the exclusion of a potential immediate physical response of PM levels to the earthquake through soil resuspension, combined high-resolution time-series analysis and baseline comparison provide no evidence of an immediate particulate matter response coincident with the arrival of seismic waves. Further, overall PM levels in all size fractions recorded after 11:00 pm (local time) on 8 September and during the first hour of 9 September remain within or even sink below the interquartile range of the established baseline, indicating that observed levels are consistent with typical diurnal variability at both the urban and background sampling site and reflecting a low-pollution scenario.

Observable changes in PM concentrations emerge several hours later at both the urban and the background sites, manifesting as unusually high peak values. At the background site, the impact is more pronounced on 9 September with a complete inversion of the typical diurnal cycle. High hourly concentrations are observed during nighttime, followed by the minimum observed during the typical morning rush hour, and increase from noon to early afternoon (Figure S8). The daily maximum, typically attributed to morning activities at around 8 am, was observed at 3 am with values well above the upper limit of

the IQR. A second peak was exhibited between 2 and 4 pm, and a third one between 5 and 7 pm, a period which generally corresponds to daily minimal concentrations. During the evening of 9 September and the night and morning of 10 September, concentrations remained stably high, but without exceeding the IQR, and following the typical diurnal cycle. Post-seismic PM levels at the urban site exhibited similar behaviour as at the background site, with multiple peaks exceeding the typical range delimited by the IQR of the baseline distributions over the first two days after the earthquake. Nevertheless, the typical diurnal cycle remains intact at the urban site (Figure S10), which is due to the inherently higher hourly mean concentrations as well as the larger diurnal and point-to-point fluctuations, which increase the spread of typically measured daily values.

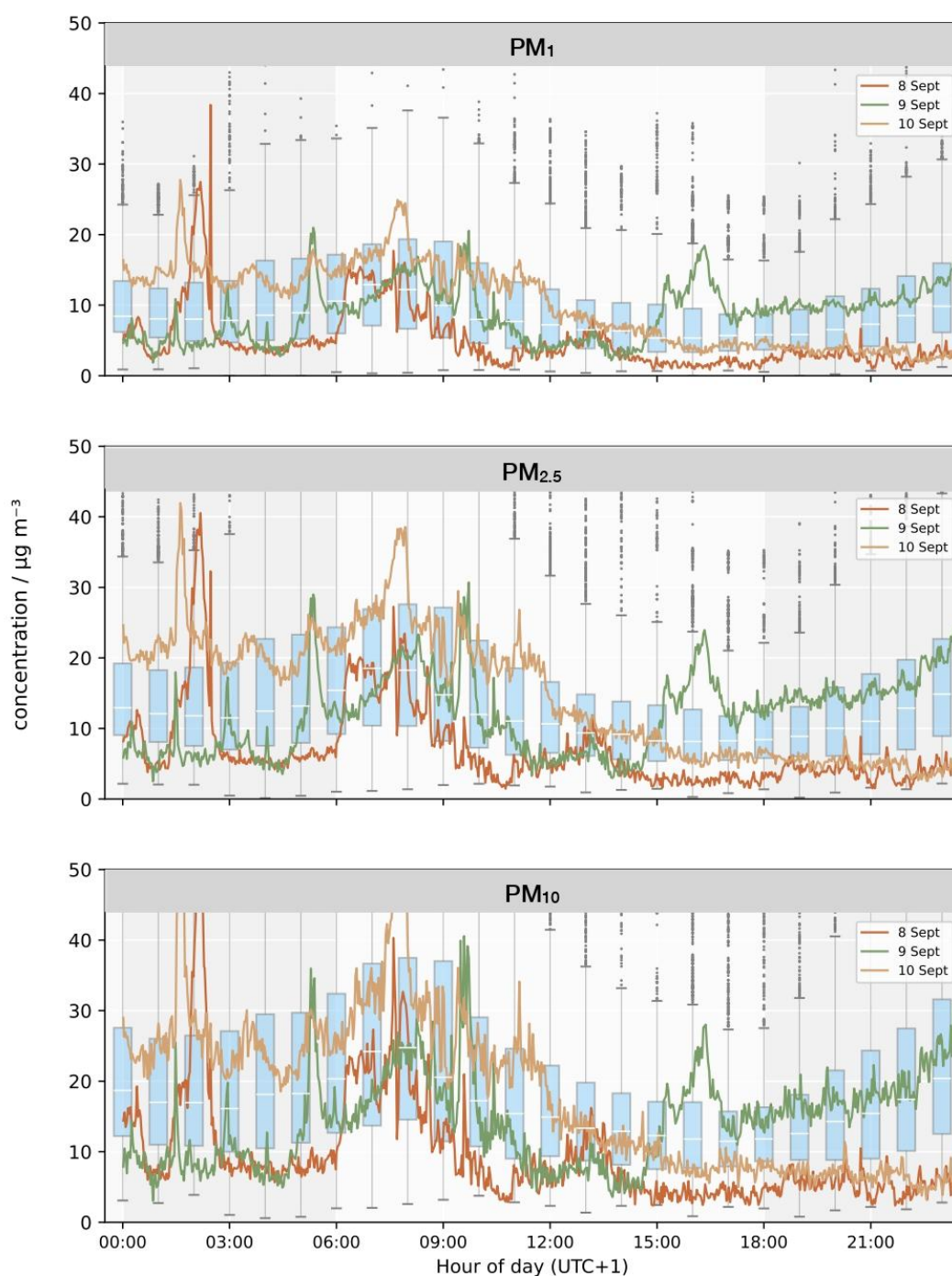


Figure 9. PM_{10} , $PM_{2.5}$, and PM_{10} mass concentration time series at the urban site for 8 September (red), 9 September (green), and 10 September (ochre) overlayed with the baseline levels represented by

boxplots of hourly aggregated PM observations from September 2023, excluding the days of analysis. Boxes show 25th–75th percentiles of hourly concentrations from all September days except 8 and 10 September.

The delayed perturbations observed at both sites are linked to indirect anthropogenic responses, particularly intensified traffic and population mobility following the seismic event. The time-series data also indicate that the atmospheric impact of the Al Haouz earthquake was not limited to a single and short-lived pulse but rather a two-stage perturbation in PM concentrations lasting nearly 48 h, each reflecting a different physical and behavioural driver. The first stage, following the main quake, can be identified during the late night and early morning hours of 9 September, and can be associated with human responses to the news of the earthquake, resulting in increased nighttime mobility and consequently increased vehicle use, leading to enhanced traffic emissions and aerosols. A second stage emerges in the afternoon of 9 September. It can potentially be linked to a second wave of increased mobility: likely people and emergency aid leaving for the Al Haouz region. It is noteworthy that instead of a rapid return to baseline conditions after these stages, PM levels remained elevated and variable until the end of 10 September, and even further as indicated by comparison of the PM_{2.5} distributions in Figures 7 and 8. These determined PM levels are likely related to sustained secondary resuspension processes, driven by intense traffic activity during the weekend. In fact, in the subsequent days, increased vehicle movement (such as associated with residents checking on family members and departures of emergency aid convoys) likely acted as a continuous source of traffic-induced dust resuspension, extending the atmospheric perturbations beyond the initial earthquake episode rather than reflecting a single and short-lived event. On top of anthropogenic emissions related to increased mobility stemming from the immediate reaction of the population to the earthquake, we must acknowledge that long-range atmospheric transport from the active fault zone, where air pollution levels remain persistently high after the earthquake, might also have significant impacts on the air-quality following the seismic activity on timescales longer than the few days analysed in detail in this study. Even though the 4-day HYSPLIT backward trajectory analyses indicate that the air masses reaching the study area during the immediate post-seismic period predominantly originated from the North Atlantic and western maritime sector, rather than from the Al Haouz epicentral region (Figure S11), the persistence of higher PM levels for over a week, as revealed by the impact analysis, suggests that a delayed contribution from long-range atmospheric transport cannot be excluded, and needs to be studied by simulations spanning longer timescales.

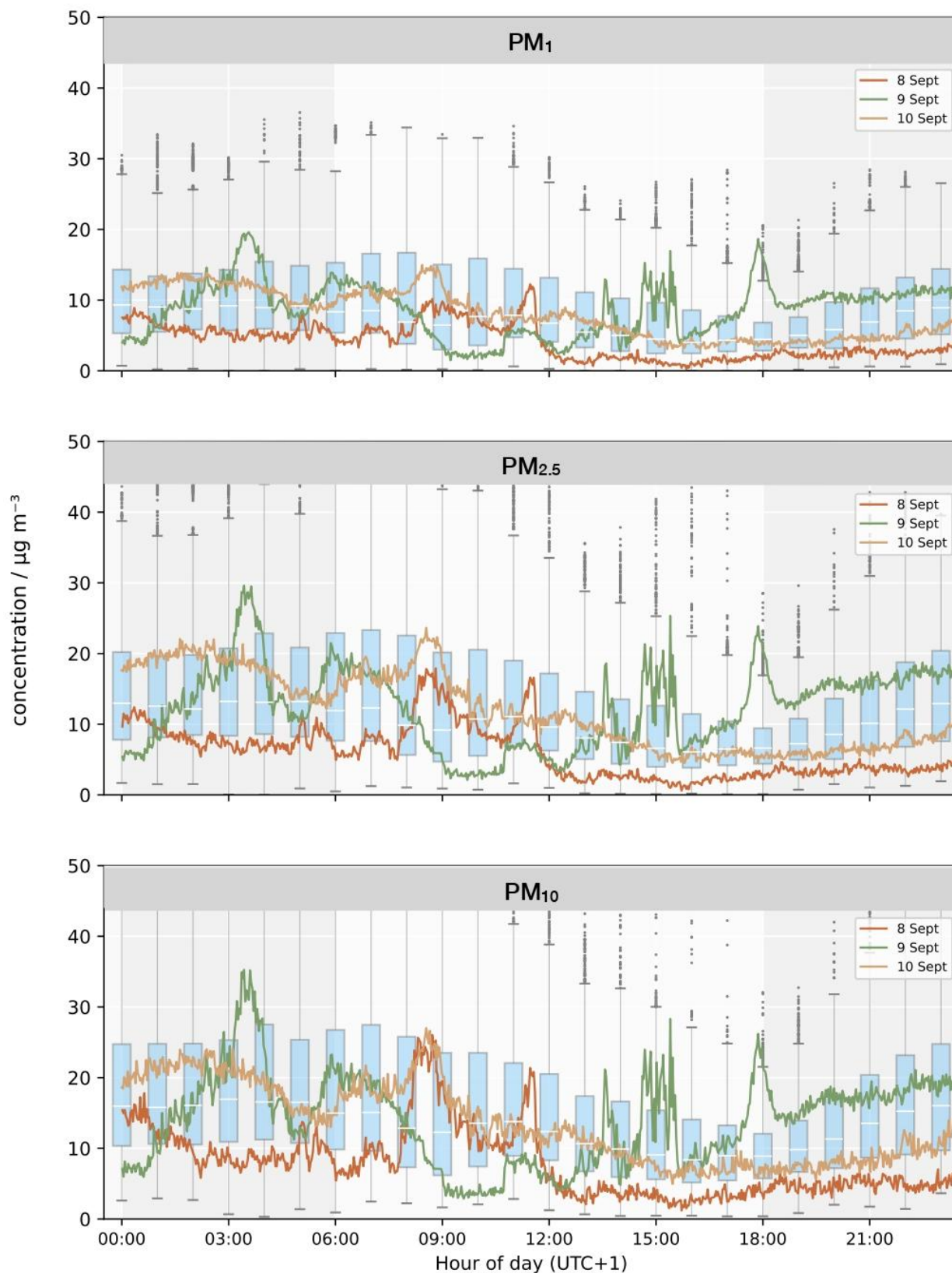


Figure 10. PM_{10} , $PM_{2.5}$, and PM_{10} mass concentration time series at the background site for 8 September (red), 9 September (green), and 10 September (ochre) overlaid with the baseline levels represented by boxplots of hourly aggregated PM observations from September 2023, excluding the days of analysis. Boxes show 25th–75th percentiles of hourly concentrations from all September days except 8 and 10 September.

4. Conclusions

This study demonstrates that the 8 September 2023 Al Haouz earthquake acted as a significant driver of urban air quality variability in cities located far beyond the epicentre region. High-temporal-resolution measurements of particulate matter (PM₁, PM_{2.5}, and PM₁₀) and gaseous pollutants (NO₂ and CO) collected in both urban and background locations situated hundreds of kilometres from the epicentre, revealed distinct deviations from typical diurnal cycles. These changes included shifts in the diurnal patterns, unexpected concentration increases, multi-peak structures, and enhanced short-term variability. These perturbations indicate a decoupling between routine urban emission patterns and externally forced human mobility. High-resolution statistical analyses and model calculations further confirm that no immediate particulate matter anomaly coincided with the seismic waves' arrival, reinforcing the interpretation that the observed air-quality changes were primarily driven by post-seismic human mobility rather than direct mechanical resuspension. Instead of being dominated by direct seismic emissions, the observed air quality changes are best interpreted as indirect effects associated with human behaviour, such as mass displacement, aftershock-driven mobility, and large-scale return-home traffic. Post-seismic enhancements in particulate matter highlight emergency-driven mobility as an efficient, yet short-lived, driver of traffic-induced dust resuspension and increased anthropogenic emissions. The pronounced multi-peak responses of NO₂ reflect its strong sensitivity to sudden shifts in traffic-related activity. Indeed, the contrasting responses of particulate matter and traffic-related gaseous pollutants highlight the sensitivity of urban air quality to sudden changes in mobility and surface perturbations, even in regions distant from the seismic source. Nevertheless, the rapid attenuation of these perturbations and the recovery of typical diurnal cycles within approximately one to two days suggests a capacity of urban atmospheric systems to re-equilibrate once emergency-driven activity subsides. Overall, these findings emphasise that the high-resolution air quality observations can serve as an indirect and real-time indicator of societal response to extreme events.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos17070679/s1>, Figure S1: Three-component continuous seismogram recorded at the RTC (Rabat) broadband station during the 8 September 2023 Al Haouz earthquake. The record displays high-gain velocity channels (HHZ, HHE, and HHN) over a three-hour window between 9:00 pm and midnight UTC (UTC+1 in local time), illustrating the temporal evolution of seismic amplitudes leading up to and following the main shock. Figure S2. Seismic recording of the Al Haouz earthquake at the RTC station illustrating the temporal parameters of the event, including T₀ (origin time) and the arrival times of the seismic phases (P, S, etc.); Figure S3. Ratios and differences in the different PM mass fractions at the urban site recorded over two months from 1 September 2023 to 30 October 2023; Figure S4. Ratios and differences in the different PM mass fractions at the background site recorded over two months from 1 September 2023 to 30 October 2023; Figure S5. Time series of PM_{2.5} concentrations in September 2023. Blue lines show the raw output of the Purple Air sensor and red lines indicate the time series obtained after applying a correction for the impact of relative humidity on the measurements. The corrected time series were computed by the following formula: $PM_{2.5,corr} = 0.52 \times PM_{2.5,obs} - 0.086 \times RH + 5.75$ [62]; Figure S6. ERA5-Land meteorological fields corresponding to the four principal phases of the post-earthquake air-quality response identified in this study: (a) pre-earthquake reference conditions, (b) immediate evacuation period, (c) aftershock-related period, and (d) morning return-home period. The upper panels show 2 m temperature, relative humidity, while the lower panels, show wind gust and planetary boundary layer height. No unusual synoptic-scale meteorological conditions are evident during the periods associated with the observed pollutant anomalies; Figure S7. Impact analysis boxplots comparing pre- and post-seismic PM distributions at multiple timescales for the urban

site (Salé). From top to bottom: 1-h timescale (panel 1), 1-day timescale (panel 2), 2-day timescale (panel 3), and 1-week timescale (panel 4); Figure S8. Impact analysis boxplots comparing pre- and post-seismic PM distributions at multiple (hourly, daily, bi-daily, and weekly) timescales for the background site. From top to bottom: 1-h timescale (panel 1), 1-day timescale (panel 2), 2-day timescale (panel 3), and 1-week timescale (panel 4); Figure S9. Comparison of the diurnal cycle of PM concentrations the day before and after the earthquake at the background site, Maamoura; Figure S10. Comparison of the diurnal cycle of PM concentrations, the day before and after the earthquake at the urban site, Salé; Figure S11. NOAA HYSPLIT backward trajectories ending at the Salé and Maamoura receptor sites (black star) on 10 September 2023 at 06:00 UTC (panel 1) and 10 September 2023 at 00:00 UTC (panel 2), computed over 96 h using GDAS meteorological data. Trajectories are shown for three arrival heights: 500 m, 1000 m, and 1500 m above ground level (AGL). The trajectories indicate that the air masses reaching the study areas during the post-seismic period mainly originated from the western maritime sector, with no direct transport pathway from the Al Haouz epicentral region; Table S1. Characteristics of the air quality monitoring sites used in this study, including site classification, geographical coordinates, measured pollutants, and sampling time resolution. All three air masses are predominantly advected northward and northeastward over the Iberian Peninsula and into central Europe.

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