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Mortality associated with compound exposure to heat and ozone across five Moroccan regions

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Abstract

Background: Compound heat-ozone events are projected to become more frequent and intense under climate change, with North Africa among the most exposed regions, yet evidence from this region remains scarce.

Methods: To quantify pooled and region-specific excess mortality associated with heat, ozone, and their co-occurrence across five Moroccan regions in 2021. We used a time-stratified case-crossover analysis of daily all-cause mortality using conditional quasi-Poisson models. Extreme heat and ozone were defined as days with maximum temperature (Tmax) and maximum daily 8-h

average ozone (MDA8) $\geq 90^{\text{th}}$ of region-specific percentile, and compound heat-ozone events as same-day co-exceedance or higher ozone within the subsequent.

Results: In the pooled analysis, heat-only and compound events were associated with statistically significant excess mortality (RR=1.18, 95% CI:1.11-1.1.25 and RR=1.16, 95% CI:1.10-1.22 respectively), ozone-only days showed no statistically significant excess mortality. The region-specific analysis showed a substantial heterogeneity, with Oriental was the only region with significant associations across all exposures. A significant heat-only association was also found in Tanger-Tétouan-Al Hoceima (RR=1.22, 95% CI: 1.11-1.35). The analysis of interaction metrics showed no sign of synergistic interaction between heat and ozone. Results were stable across different lag specifications and sensitivity analysis excluding extreme COVID-19 periods and individual regions.

Conclusion: extreme heat alone or compounded with high ozone was associated with excess mortality in Morocco. This risk was spatial heterogeneous and not amplified by ozone. These results support region-specific early warning system and stress the need for longer time series to refine compound exposures risk estimates

Key words: Compound, Heat, Ozone, Mortality

Introduction

Global warming is increasing the frequency, intensity, and duration of heatwave episodes, with well-documented consequences for population health (Calvin et al. 2023; Romanello et al. 2024; Bell, Gasparri, and Benjamin 2024). Extreme heat has been linked to major short-term mortality shocks, including more than 2 500 deaths during the in 2015 heatwave in India, around 56 000 deaths during the 2010 heatwave in Russia, and an estimated 61 672 heat-related deaths across

Europe during the summer of 2022 (Ballester et al. 2023; India Faces Deadly Heat Wave - NASA Science 2015; Maksimenko et al. 2024). concurrently, air pollution remains a global threat: nearly 99% of the global population breathed air exceeding the World Health Organization (WHO) air quality limits, with populations from low- and middle-income countries (LMICs) being the most exposed (WHO Ambient Air Quality Database, 2022 Update 2023; Rentschler and Leonova 2023). Recent literature recognizes heat and ground-level ozone not as independent hazards but as frequently co-occurring exposures, with shared meteorological drivers and possible joint burden on human health (Schnell and Prather 2017).

Multiple meteorological and chemical drivers lead to compound heat and ozone events: First, high temperatures accelerate photochemical ozone production from nitrogen oxides and volatile organic compounds under high solar radiation (N. Wang et al. 2026). Second, stagnant atmospheric conditions characterized by low wind speeds, shallow boundary layer and persistent high-pressure systems limit pollutant dispersion and favor pollutants accumulation including ozone and its precursors (Horton, Harshvardhan, and Diffenbaugh 2012; Hu et al. 2012). Third, low humidity and dry can enhances photochemical ozone formation of and limits its reduction through moisture-related elimination pathways (Kavassalis and Murphy 2017). Urban environments could increase the occurrence of compound heat-ozone events through urban heat islands effect (Song et al. 2024). Together, these mechanisms are likely to be reinforced by climate change, which is expected to increase the frequency and intensity of these compound hazards (Intergovernmental Panel On Climate Change (Ipcc) 2023a). Furthermore, under a high-emissions scenario, projections indicate an average increase of 34.6 compound event days per year in 2071-2090, with greater impact in LMICs (Ban et al. 2022).

Beyond their environmental drivers, heat and ozone are associated with an inflammatory oxidative burden on the human body through overlapping biological mechanisms (Enweasor, Flayer, and Haczku 2021; J. Xu et al. 2025). Heat stress elevates the core body temperature, triggering dehydration and hemoconcentration, which can promote the release pro-inflammatory cytokines, leading to a higher vascular inflammatory response (J. Xu et al. 2025). Similarly, ozone exposure is associated with respiratory tissue injury and a localized inflammatory response evolving to systemic inflammation after the release of inflammatory mediators and oxidative products into the circulation (Enweasor, Flayer, and Haczku 2021; Wiegman et al. 2020). On the basis of these shared mechanisms, experimental animal studies and some epidemiological analyses suggest that co-exposure to heat and ozone acts synergistically, amplifying the shared inflammatory load of both hazards and result in higher health impact during compound events (Grigorieva and Lukyanets 2021; Ro 2025; Wei et al. 2025; F. Xu et al. 2023). However, the detection of this synergistic effect at population level particularly outside high-income settings remains uncertain (Y. Wang et al. 2026a).

According to the World Meteorological Organization, the Middle East and North Africa region is warming at twice the global average, with intensifying heatwave events ((State of the Global Climate 2024 2025). Similarly, Morocco exemplifies this trajectory, having experienced a warming trend of +0.33°C per decade over 1984-2016 (Driouech et al. 2021). National estimates project a continued warming across scenarios, under high-emissions scenario the average annual temperature in Morocco potentially rising by 2-3°C by 2100 under a high emissions pathway (National Climate Resilience Assessment for Morocco – Analysis 2023). Simultaneously, observational and modelling studies from multiple areas in Morocco have reported recurrent exceedances of WHO ozone guideline values (Imane et al. 2022). Sekmoudi et al. reported that

higher air pollution levels in Kenitra, Casablanca, and Essaouira, identifying road traffic as the primary source, followed by industrial activities (Imane et al. 2022). Finally, these trends suggest that Moroccan population is increasingly exposed to heat, ozone, and their co-occurrence (Khomsi et al. 2022).

Despite the growing global interest in quantifying the health impacts of compound heat-ozone events particularly in China, Europe, and North America, evidence from Arab and North African countries remains limited (Adarbaz et al. 2025; Y. Wang et al. 2026b). In Morocco only one study to date by Khomsi et al. conducted a detailed analysis of compound heat-ozone events during the extended summers between 2010 and 2019, and found that hot extremes and high ozone episodes frequently clustered in time, with ozone extremes often occurring on the first day of heatwave or offset by two days (Khomsi et al. 2022). That study, was limited to descriptive characterization of the meteorological and chemical co-occurrence and did not quantify associated mortality.

To the best of our knowledge, no study has yet estimated daily mortality risks attributable to compound heat-ozone events in Morocco. Previous studies either used descriptive meteorological analyses or assessed a single exposure time series. This study therefore aimed to explore the independent and joint impacts of heat-ozone on all-cause mortality across five Moroccan regions.

Methods

Study population

All-cause mortality data was obtained from the Ministry of Health and Social Protection as part of the first outputs of the newly implemented electronic mortality records, introduced within a long series of reforms of Civil Registration and Vital Statistics in Morocco. The dataset contained daily

all-cause mortality counts of mortality in five regions in Morocco: Rabat-Salé-Kénitra, Tanger-Tétouan-Al Hoceima, Marrakech-Safi, Sous-Massa, and Oriental, covering the period 01/01/2021 to 31/12/2021. Together, these five regions included 19.37 million residents and 52.6% of Morocco's legal population.

The five Moroccan study regions are geographically and climatically heterogeneous, Rabat-Salé-Kénitra is in the northwest and is influenced by Atlantic coastal conditions. Tanger-Tétouan-Al Hoceima is in the north and is influenced by Mediterranean and Atlantic conditions. Marrakech-Safi is in west-central with and includes a mix of semi-arid and Atlantic conditions. Sous-Massa is situated in the southwest and represents a transition from Atlantic to Saharan conditions. Oriental, in the northeast, influenced by Mediterranean in north and semi-arid conditions inland areas.

Exposure assessment

Meteorological variables were obtained from the ERA5 reanalysis via the Copernicus Climate Data Store of the European Center for Medium-Range Weather Forecasts. We extracted hourly 2-m air temperature and processed it using Climate Data Operators. To compute the daily maximum temperature (Tmax) for each grid cell, we interpolated the fields to a 0.25°x0.25° grid to ensure variable consistency, then averaged the maximum temperature across all grid cells whose centroids fell within regional boundaries to create a daily regional Tmax series for 2021.

Daily surface ozone exposure was obtained from the Global Land Daily 10 km Surface Ozone Dataset, which provides gridded MDA8 ozone estimates produced using a Light Gradient Boosting Machine model integrating reanalysis, satellite, observation, and chemical model data. We

extracted the 2021 daily MDA8 ozone and computed region-level daily ozone time series following the same grid interpolation ($0.25^\circ \times 0.25^\circ$) used in calculating Tmax.

We calculated region-specific empirical 90th percentiles using the 2021 distributions of temperature and MDA 8 ozone. This non-parametric approach was used to capture rare high-exposure days. Heat days were defined as days with Tmax greater than or equal to the region-specific 90th percentile sustained for at least three consecutive days. High ozone days were defined as days with MDA8 greater than or equal to the region-specific 90th percentile. Compound events were defined as same-day co-occurrence of a heat and a high ozone, or high ozone exceedance occurring within the subsequent two days following a first heat exceedance day. This compound definition is supported by Morocco-specific evidence from Khomsi et al. (2022), who reported that high ozone episodes occur on the first heat day or with a short time offset (Khomsi et al. 2022). Following the present definition of compound events, we created four categories: (i) no exposure (reference), (ii) heat only, (iii) ozone only, and (iv) compound heat and ozone.

Statistical analysis

We quantified the daily variation in all-cause mortality associated with extreme heat, high MDA8 ozone, and compound exposure events using a time-stratified design. Daily mortality counts were modelled using generalized linear models with a quasi-Poisson distribution account for the over-dispersion in daily mortality, which is a standard approach for categorical heat and air pollution time series analysis.

To control for seasonality, region, and weekly patterns, the model incorporated a stratum term defined by the interaction of region, calendar, month, and day of the week. Our model compares mortality on exposed versus unexposed days within the same region, month, and day of the week,

removing confounding by season, region baseline mortality, and day-of the week effects by design. To control for the influence of the COVID-19 pandemic on mortality, we adjusted our model for a 7-day moving average of national daily COVID-19 deaths. The model was as follows:

$$\log(\mu_{rt}) = \beta_1 I(HeatOnly_{rt}) + \beta_2 I(OzoneOnly_{rt}) + \beta_3 I(Compound_{rt}) + \theta COVID_t + S(r, m, dow)$$

(μ_{rt}) is the expected number of deaths on day t in region r , $I(.)$ are indicator variables for the heat only, ozone-only, and compound exposure categories. $\beta_1, \beta_2, \beta_3$, are the corresponding log rate ratios, $COVID_t$ is the 7-day moving average of national daily COVID-19 deaths and θ is its coefficient, $S(r, m, dow)$ is the fixed effect (stratum) for each region x month x day of the week combination.

We estimated both a pooled association across five regions and region-specific associations fitted separately within each region. We used a cumulative lag 0-1 exposure specification accounting for exposure on the same day or the preceding day. To the synergistic interaction between both exposures we computed three additive interaction metrics, relative excess risk due to interaction (RERI), attributable proportion (AP), and the synergy index (SI) from the estimated ratios. Confidence intervals for these metrics were calculated using a stratum-block bootstrap with 2000 resamples.

Sensitivity analysis

We examined the robustness of our pooled association estimate using multiples sensitivity analyses. We examined alternative lag specifications, including single-day lag (1-3) and cumulative lag windows (lag0-3, lag 0-7). We evaluated the influence of the summer season and

COVID-19 pandemic by re-estimating the primary model after excluding July and August, days with more than 50 and more 100 daily COVID-19 deaths. Finally, we sequentially removed each region from the model and re-estimate ratios to assess region-specific influence on the pooled compound events estimate. Our analyses were conducted using R version 4.5.2 (2025-10-31).

Results

Descriptive statistics of the mortality and exposures

Table 1 presents the summary of descriptive statistics of mortality, temperature, and ozone by regions. In 2021, a total of 67 758 all-cause deaths were recorded in Morocco's five study regions, with substantial inter-regional variation. The highest total mortality was reported in Tanger-Tétouan-Al Hoceima (20 058 deaths, mean=55.0 deaths/day), followed by Souss-Massa (17 194, mean= 47.1 deaths/day). The lowest total deaths were reported in Marrakech-Safi (9 147, mean= 25.1 deaths/day). Day-to-day variability was moderate, with a standard deviation ranging from 11.5 to 14.3 deaths. The maximum daily deaths ranged from 103 deaths in Souss-Massa to 73 deaths in Marrakech, while the minimum mortality ranged from 5 deaths in Rabat-Salé-Kénitra to 23 deaths in Souss-Massa (Table 1 in supplementary materials).

Regarding temperature, the 90th percentile of the mean daily maximum temperature (T_{max}) varied across regions, with the highest value in Sous-Massa (27.1°C), followed by the Oriental (24.8°C). The lowest mean T_{max} threshold was observed in Tanger-Tétouan-Al Hoceima (21.8°C). Similarly, the 90th percentile of mean MDA8 ozone concentrations varied across regions, ranged from 86.2 µg/ m³ in Souss Massa to 75.4 µg/m³ in Rabat-Salé-Kénitra.

The daily exposure calendar is presented in the fig 2 in supplementary materials, each day was classified as reference day for heatwave, ozone, and compound event. The reference days constituted most study days across all regions. High ozone days showed a broad seasonal distribution occurring from April October, while heatwave days and compound events were concentrated to warm season from July to September across all regions. The number of compound events ranged between 16 in Sous Massa to 22 in Oriental, with Rabat-Salé-Kénitra and Tanger-Tétouan-Al Hoceima each recoding 20 compound days and Marrakech-Safi.

Table 1: Descriptive statistics by region

Region	Mortality				Temperature		Ozone (MDA8)	
	Days	Total deaths	Mean daily deaths	Sd daily deaths	Mean Tmax(°C)	P90 Tmax(°c)	Mean MDA8 O3 (µg/m3)	P90 MDA8 O3 (µg/m3)
Marrakech	365	9434	25.1	11.5	24.7	32.1	81.1	93.9
Safi								
Oriental	365	8792	27.6	14.1	24.8	36	85.8	100.3
Rabat Sale								
Kenitra	365	19165	30.9	14.3	23.7	30.7	75.4	87.1
Souss								
Massa	365	5217	47.1	13.8	27.1	36.3	86.2	99.7
Tangier								
Tétouan	365	10792	55	13.7	21.8	29.1	78.2	90.6
AlHoceim								
a								

Impact of single and compound hazards on mortality

205

206 Figure 1 presents the region-specific and pooled rate ratio estimates for all-cause mortality
 207 associated with heatwave only, ozone only, and compound events. For heat wave days, only three
 208 regions showed estimates at or below the null, with wide confidence intervals. Oriental (RR=1.37,
 209 95% CI: 1.17-1.61) and Tanger-Tétouan-Al Hoceima (RR= 1.22, 95% CI: 1.11-1.35) showed a
 210 statistically significant excess mortality. In contrast, Marrakech-Safi, Rabat-Salé-Kénitra, and
 211 Souss Massa showed estimates close to the null. The Pooled heat wave estimate was statistically
 212 significant (RR= 1.18, 95% CI: 1.11-1.25). For ozone only days four of the five regions were
 213 clustered near the null. Similarly, the pooled estimate showed no excess mortality risk (RR= 1.02,
 214 95% CI: 0.978-1.064). In contrary, only Oriental's estimates showed a statistically significant
 215 ozone-related mortality risk (RR= 1.18, 95% CI: 1.04-1.33).

216 The pooled compound events estimate shows a statistically significant excess mortality risk (RR=
 217 1.16, 95% CI: 1.10-1.22) representing a 15.7% excess all-cause mortality risk on days of
 218 simultaneous extreme heat and ozone. The region-specific estimates were near to the null with
 219 wide confidence intervals in Marrakech-Safi, Rabat-Salé-Kénitra, Sous-Massa, and Tange-
 220 Tétouan-Al Hoceima (RR range: 1.03-1.085). In contrast, compound estimates were statistically
 221 significant (RR=1.64, 95% CI: 1.42-1.90).

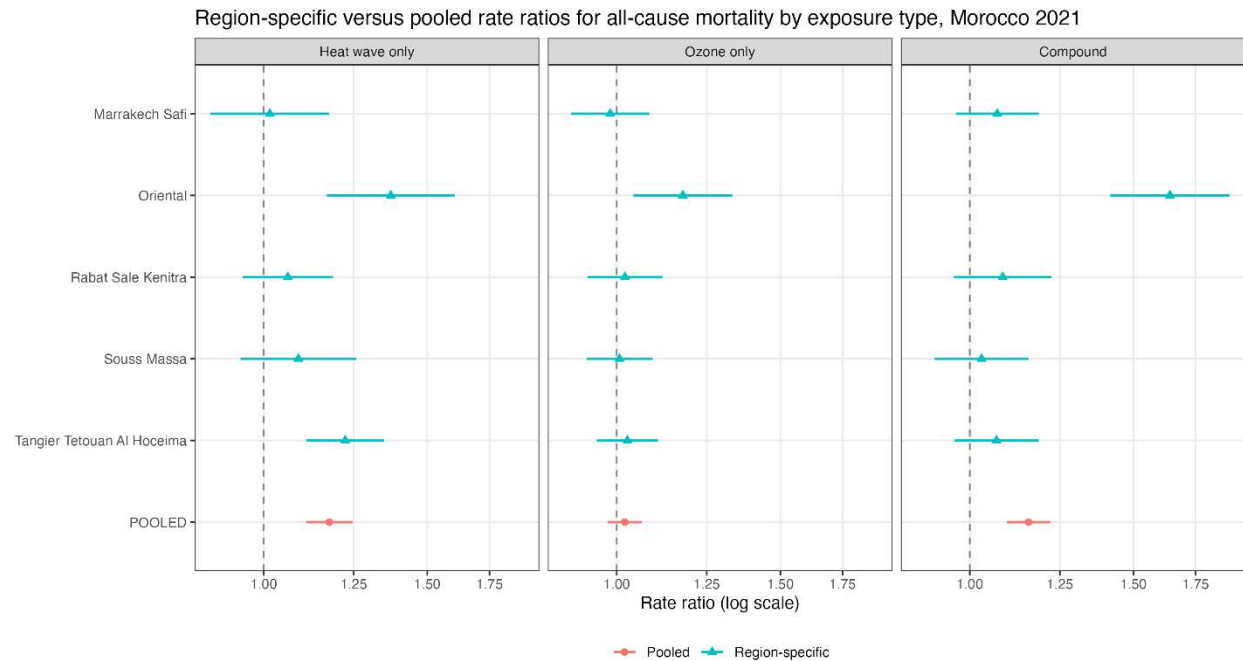


Figure 1: region-specific vs pooled rate ratios for mortality by exposure

Mortality risk by exposure and lag

Figure 2 presents the pooled rate ratio estimates for heat only, ozone only and compound events across the three primary lag specifications (lag0, lag1, and cumulative lag0-1). Across the three lag specifications heat only days and compound events were associated with statistically significant excess mortality, while ozone only days showed no independent association across any lag specification (RR=1.02, 95% CI: 0.98-1.06). Heatwave days and compound events were associated with a 17.7% (RR=1.18, 95% CI: 1.11-1.25) and 15.7% (RR= 1.19, 95% CI: 1.10-1.22) excess mortality, respectively.

Figure 2 in supplementary materials presents the sensitivity of the heat wave days and compound events associations to the choice of lag specification, split to single and cumulative lags. Across

single day lags the association of both exposures with mortality was higher at lag 0 and decline gradually at longer lags. The risk of heat wave only declining steeply from RR=1.17, 95% CI:1.10-1.23 at lag 0 to RR=1.04, 95% CI: 0.98-1.10 at lag 3, while the risk of compound events declined from RR=1.15 95% CI: 1.08-1.22 at lag 0 RR=1.10, 95% CI: 1.03-1.17 at lag 3. This pattern suggests that compound exposure produces a more sustained mortality effect than heat alone. The cumulative lags estimate show that both exposures remained statistically significant from lag 0-1 through lag 0-7. Heat wave only passed from RR=1.17 95% CI:1.11- 1.24 at lag 0-1 to RR=1.12 95% CI:1.05-1.19 at lag 0-7, while compound events passed from RR=1.15 95% CI: 1.09-1.22 at lag 0-1 to RR= 1.09 95% CI: 1.04-1.15 at lag 0-7, which suggests that observed associations reflect genuine excess mortality rather than a short-term mortality displacement.

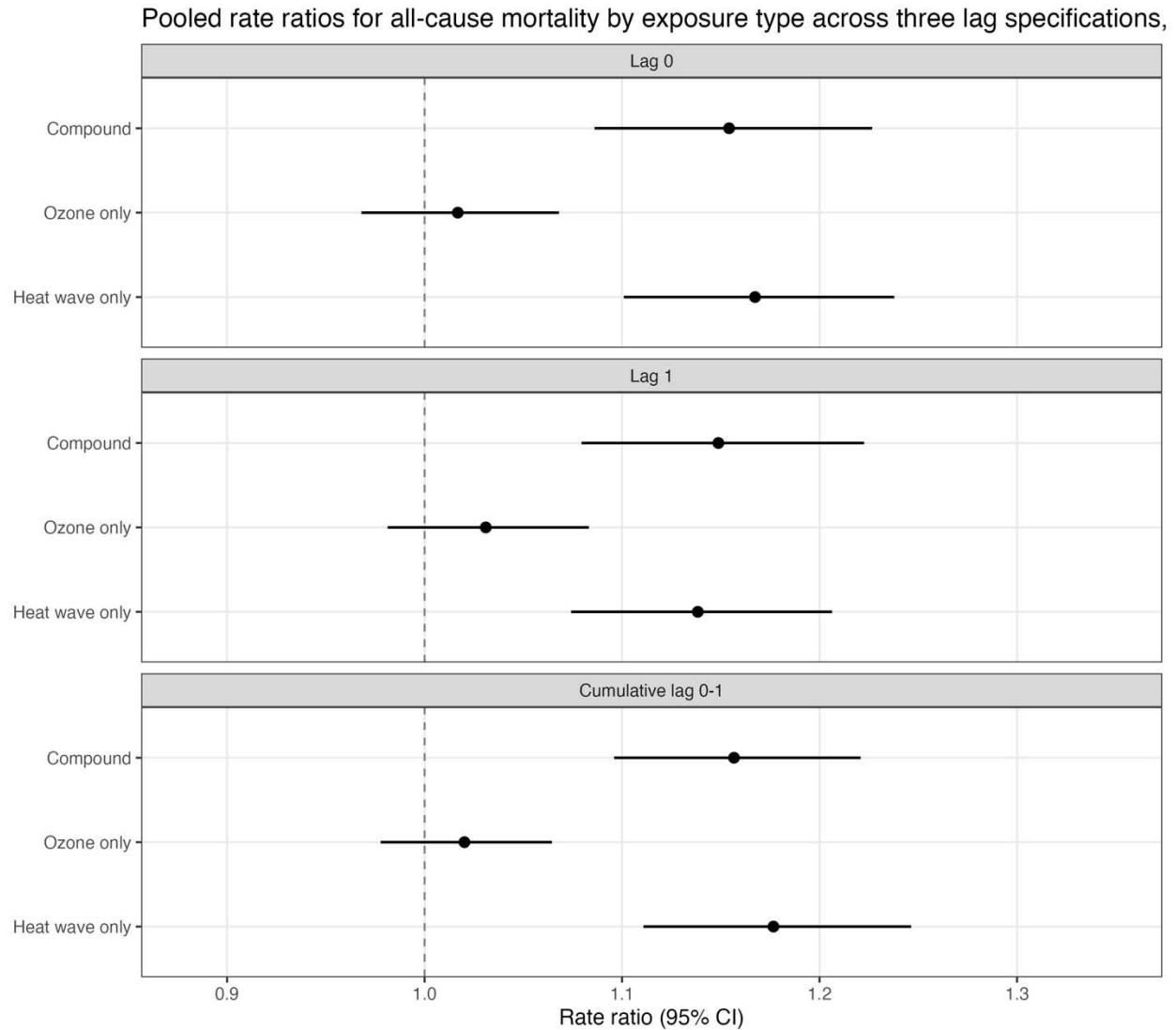


Figure 2: Pooled estimates by exposures and lag specifications.

Heat and ozone analysis

To examine the existence of a synergistic effect of heat and ozone on mortality beyond their individual contributions, we estimated the relative excess risk to interaction (RERI), the attributable proportion (AP), and the synergy index (SI) across the three primary lag specifications

(table 2 supplementary materials). Consistently across lag specifications, RERI values were small and negative (lag0-1 RERI= -0.040, 95% CI: -0.143 -0.050). Similarly, the AP point estimates were all negative ranging from AP= -0.026, 95% CI: -0.11 – 0.06 in lag 0 to AP= – 0.035, 95% CI: - 0.12-0.04. The RERI, AP, and SI showed an additivity across all lag specifications, indicating no super-additive interaction between heat and ozone on all-cause mortality.

Sensitivity and robustness analyses

The figure 3 present a series of sensitivity and robustness analyses of the primary compound events association with mortality. during these analyses we excluded specific month, season, high COVID-19 period, and certain regions. The exclusion of August attenuated the estimate (RR=1.04, 95% CI:0.95-1.12) as did the exclusion of the July and August combined (RR=0.97, 95% CI: 0.81-1.17). These seasonal attenuations are expected, because compound events were concentrated in July and August. Excluding the summer months removes most compound days leaving too few informative strata required to estimate the association. The association was robust to the exclusion of the extreme COVID-19 mortality days, removing days with more than 100 daily COVID-19 mortality did not affect the mortality risk (RR=1.18, 95% CI: 1.10-1.27). In contrast, removing days with more than 50 COVID-19 deaths reduced the point estimate and was not statistically not significant (RR=1.04, 95% CI:0.96-1.14).

In the leave out one region out analyses (LOO), the compound events related mortality risk was statically significant and above the null when each of Souss-Massa (RR=1.20, 95% CI:1.13-1.127), Tanger-Tétouan-Al Hoceima (RR=1.19, 95% CI:1.12-1.27), Rabat-Salé-Kénitra (RR=1.18, 95% CI:1.11-1.25), and Marrakech-Safi (RR=1.17, 95% CI:1.10-1.24) was

sequentially excluded, showing that none of these regions influenced the pooled estimate. In contrary, excluding Oriental reduced the estimated to $RR=1.06$, 95% CI:1.00-1.12, highlighting that Oriental was the main driver of the compound event mortality signal. Overall, these analyses showcase that primary compound event association is robust across analytical specifications, with attenuation occurring only under warm months and Oriental exclusion. We used a less extreme region-specific 75th percentile ozone threshold, to assess the effect of compound definitions on our estimate, the association was unchanged ($RR= 1.15$, 95% CI: 1.10-1.21).

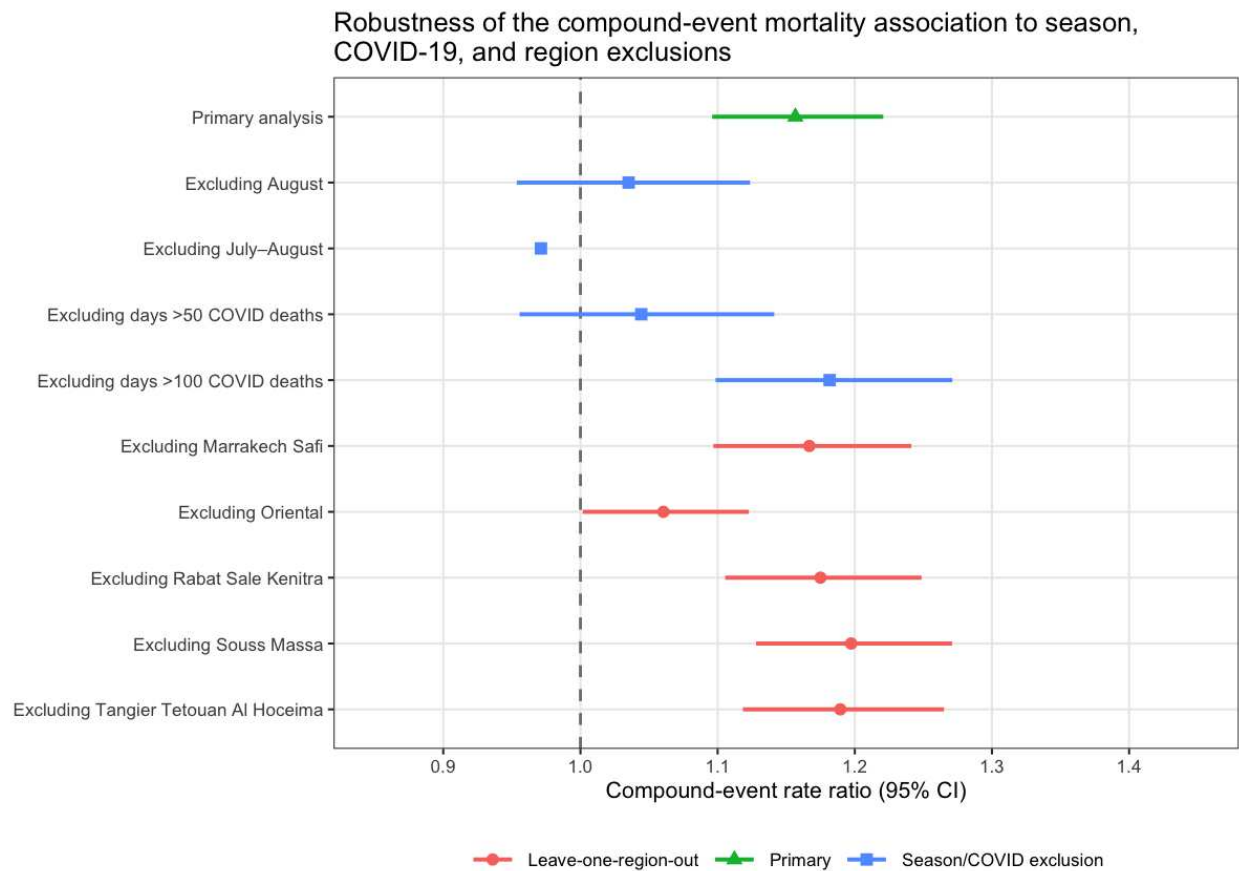


Figure 3: Robustness of the compound event mortality association

Discussion

This study quantified the associations of extreme heat, elevated ozone, and their co-occurrence across five administrative regions of Morocco during 2021. Using region-specific 90th percentiles thresholds of maximum temperature and MDA8 ozone. In the pooled analysis, both heat only and compound exposure days were associated with significant excess mortality (heat only: RR=1.18, 95% CI: 1.11-1.25; compound events RR=1.16, 95% CI: 1.10-1.22) while ozone only days did not show a significant association (RR= 1.02, 95% CI: 0.98-1.06). The pooled estimates masked a substantial regional heterogeneity, with the excess mortality signal concentrated in the Oriental region. The magnitude of the compound association did not exceed that of heat only, and test of additive interaction showed no evidence of synergy between the two exposures.

Our findings suggest that although compound events were associated with increased mortality, this excess was driven primarily by the heat exposure rather than a synergistic interaction with ozone. The RERI value were small and negative across all lag specifications (RERI= -0.04, 95% CI: -0.14-0.05) and SI showed the existence with additivity. This pattern is internally coherent because ozone-only days did not present a significant mortality risk, so the compound association tracked the heat only association. Our results differ from experimental and epidemiological studies that hypothesized about the amplification of inflammatory and oxidative burden during the co-exposure (Grigorieva and Lukyanets 2021; Ro 2025; Wei et al. 2025; F. Xu et al. 2023). The magnitude of our compound association closely matches those reported by recent systematic review and meta-analysis reporting concurrent heat and high ozone were associated with a 17% increase in all-cause mortality, while the authors of this review did not assess the additive interaction, so the reported effect cannot be distinguished if it is heat-driven or synergistic effect

(Y. Wang et al. 2026a). Moreover, the findings of Wang et al notes that their estimate varied substantially across settings and according to population conditions and vulnerability (Y. Wang et al. 2026a). The limited synergistic interaction we reported could be explained by several factors: First, the limited number of compound events with a single year limit the statistical power to detect interaction. Second, the probability that the synergistic effect is weaker in this population.

Regional heterogeneity in mortality responses to heat, ozone, and compound heat-ozone exposure, with the clearest excess mortality signals observed in the two northern regions (Tanger-Tétouan-Al Hoceima and Oriental). This spatial variability may reflect differences in demographic, environmental, and socioeconomic determinants of vulnerability (Intergovernmental Panel On Climate Change (Ipcc) 2023b; Niu et al. 2021). Demographically, Oriental has the highest proportion of older adults in the country, with 16.1% (13.8% at the nationally) of the population aged ≥ 60 years, and this share reached 18.5% in some provinces (Recensement Général de la Population et de l'Habitat 2024 2025). Tanger-Tétouan-Al Hoceima had a lower overall proportion of older adults (≥ 60 years) around 11.8%, although this share reaches 16.2% in some provinces (Recensement Général de la Population et de l'Habitat 2024 2025). Multiple studies have highlighted the increased vulnerability of older adults to heat and compound heat-ozone events, which supports a plausible population-level basis for the increased heat-related mortality observed in these two regions (Crank et al. 2024; Ma et al. 2025; Niu et al. 2021).

Environmental and climatic characteristics of Tanger-Tétouan-Al Hoceima and Oriental could influence the severity of heat-related excess mortality through heat-stress dynamics and acclimatization (Gasparrini et al. 2015). Using köppen-Geiger classification, a recent Morocco focused study indicated that Tanger-Tétouan-Al Hoceima was dominated by hot-summer Mediterranean climate, while Oriental was classified largely as semi-arid to desert conditions

(Derdouri, Murayama, and Morimoto 2023). In Mediterranean coastal settings daytime maximum temperatures can be attuned by marine influence, yet high humidity and warm nights can increase heat stress by limiting evaporative cooling and nocturnal recovery, which has been linked to increased mortality risk (Balhane et al. 2022; Bright et al. 2025; Royé et al. 2025) Consistent with the acclimatization hypothesis, evidence suggests that population in moderately hot climates may be more vulnerable to heat exposure than those in arid climates, consistent with the idea that long-term exposure to hot conditions favors behavioral and infrastructural adaption (Guo et al. 2017a). Slesinski et al. examined the effect of social inequities on exposure to heat stress and its impact on adaptive capacity in the general population, their findings suggest that socially disadvantaged groups are more exposed to heat stress and have lower adaptive capacity (Slesinski et al. 2025).

In our analysis, ozone-only days showed a unique statistically significant increase in Oriental, with no evidence of an increased mortality risk across remaining regions. Multiples studies highlight that ozone's short-term mortality effect is temperature-dependent, with ozone-related mortality risk often co-occurring with higher temperature, while ozone-only conditions showed smaller or negligible mortality risk estimates (Chen et al. 2021; Ma et al. 2025; Shi et al. 2020). The levels of ozone in Oriental are consistent with this interpretation and supports that heat is the dominant driver of mortality in compound events in this region.

Multiple methodological design choices merit discussion as they shape exposure classification and effects estimation. First, we used region-specific 90th percentile thresholds to identify days with extreme heat and ozone. This thresholding approach is used to capture relative extremes specific to each region's climate and air quality conditions and to account for acclimatization by comparing each region with its local climate norms (Guo et al. 2017b). Second, we used a single year's (2021) percentile threshold to capture soft extremes with a short return period and to capture the exposure

distribution during the study period and to avoid baseline-period dependence that impact the frequency of extreme days detected (Thomas et al. 2023). Third, we defined compound events as the same-day co-exceedance or a short lag. This definition is consistent with evidence from Khomsi et al. indicating that, in Morocco, high ozone days often occur at the first heat day or with a short offset (Khomsi et al. 2022).

Our study has some limitations that should be considered when interpreting these findings. First, the analysis was constrained by the current stage of digital consolidation of mortality records, which limited our time series to a single year (2021). This single year time series affects the statistical power, especially the number of extreme events detected, the existence and the stability of detected interactions. Second, our analysis covered five of Morocco's 12 administrative regions, each with its specific environmental, demographic, and socioeconomic conditions. Therefore, the estimated associations may not be generalizable to regions not included in this study. Third, the context of our study period was characterized by COVID-19, which may have influenced air pollution levels, population vulnerability, and health system functioning. COVID-19 mortality may also have been under-ascertained or misclassified. Although we adjusted for national COVID-19 mortality, residual confounding cannot be excluded. Fourth, the findings depend on the statistical modelling approach and the definitions of extreme heat, ozone, and compound events applied in this study. Additional analyses will be needed once longer mortality time series become available to examine the effects of these hazards with greater statistical power, and observed patterns are stable across years. Moreover, our results suggest that there is a signal of constructive collaboration between heat and ozone and increased health risk, reinforcing the need for an integrated early warning system that identifies and communicates the risk of extreme heat-ozone compound events.

381

382 **Conclusion**

383 This study examined the associations between heat-only, ozone-only, compound heat-ozone
384 events and all-cause mortality across five regions of Morocco in 2021. The pooled analysis showed
385 that heat-only and compound events were associated with significant excess mortality, while
386 ozone-only days showed no independent association. The interaction analysis showed no signal of
387 synergy between heat and ozone, with excess mortality on compound days driven by heat
388 component. The region-specific analysis showed a substantial heterogeneity, with significant
389 excess mortality in Oriental and Tanger-Tétouan-Al Hoceima. This study provides pooled and
390 region-specific estimates from Morocco of the short-term mortality impacts of heat, ozone, and
391 compound heat-ozone events, addressing a key evidence gap in compound extremes and health. A
392 principal limitation is that the analysis was constrained by the current availability of mortality
393 records, restricting the time series to a single year, which limits statistical power. Although
394 exploratory, these results suggest the potential value of an integrated early warning system that
395 anticipates and communicates joint heat-ozone health risks, especially for the most vulnerable
396 regions.

397

398 **Abbreviations**

399 Tmax : maximum temperature
400 MDA8: maximum daily 8-h average ozone
401 LMICs :Low- and Middle-Income countries
402 WHO: World Health Organization
403 RERI: Relative Excess Risk to Interaction
404 AP: Attributable proportion

405 SI: Synergy Index

406

407 **Declarations**

408 **Ethics approval and consent to participate**

409 This study was approved by the Ethics Committee of Mohammed VI University of Sciences and
410 Health, Casablanca, Morocco (Comité d'Éthique de l'Université Mohammed VI des Sciences de
411 la Santé de Casablanca), file number CE/UM6SS/33/25. The study used anonymized, aggregated
412 mortality records obtained from the Moroccan Ministry of Health.

413 **Consent for publication**

414 Not applicable

415 **Availability of data and materials**

416 The meteorological data used in this study are publicly available: ERA5 reanalysis from the
417 Copernicus Climate Data Store (<https://cds.climate.copernicus.eu>) and CAMS ozone reanalysis
418 from the Copernicus Atmosphere Data Store (<https://ads.atmosphere.copernicus.eu>). The mortality
419 data that support the findings of this study were obtained from the Moroccan Ministry of Health
420 under a data-use agreement and are not publicly available. Analysis code is available at
421 [10.5281/zenodo.21890551](https://doi.org/10.5281/zenodo.21890551)

422 **Competing interests**

423 The authors declare that they have no competing interests.

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Authors' contributions

Study conception and design M.A and K.K, data collection, Data collection J.M and AM, Data analysis, and interpretation M.A, I.I, and A.H. drafting the Manuscript M.A. Critical revision J.M, M.K, I.I, and A.M

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