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Integrated assessment of simultaneous threshold exceedance of heat, air pollution and airborne allergenic pollen across Europe

Bernice Scholten [a,*], Koen van der Sanden [b], Blaise Kelly [c], Bas Henzing [c], Anjoeka Pronk [a], W. Marty Blom [a], Lisa Klous [b], Boris R.M. Kingma [b]

[a] Research Group Risk Analysis for Products in Development, Netherlands Organisation for Applied Scientific Research, Utrecht, the Netherlands
[b] Department of Human Performance, Netherlands Organization for Applied Scientific Research, Unit Defence Safety and Security, Soesterberg, the Netherlands
[c] Department of Air Quality and Emissions Research, Netherlands Organisation for Applied Scientific Research, Utrecht, the Netherlands

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ABSTRACT

Background: Climate change is expected to elevate exposure to several environmental health risk factors, including extreme environmental temperatures, air pollution and airborne allergenic pollen. Given their interconnected effects on respiratory and cardiovascular diseases, it is crucial to evaluate these exposures simultaneously. Yet, comprehensive efforts to do so remain limited. This research aims to develop an approach using modelled data, in conjunction with health-based threshold values, to assess *whether, where and when* there is simultaneous threshold exceedance of heat, air pollution and airborne allergenic pollen in Europe.
Methods: Hourly exposure data for the three stressors were sourced from three models (air pollution: LOTOS-EUROS, pollen: Copernicus Atmosphere Monitoring Service, meteorological conditions: ECMWF) for 2021 and 2022. Thresholds for each stressor that indicate the boundary of acceptable limits were based on officially established tresholds or literature recommendations. The result is a 0.1°x0.1° resolution grid (approximately 10 km x 10 km) for each stressor, with each cell representing whether exposure met or exceeded the threshold.
Findings: Simultaneous threshold exceedance of air pollution and heat is occurring in various degrees throughout Europe. In the summer of 2022, the exceedances ranged from below 1% in large parts of Northern Europe to as much as 25% of the time in the Mediterranean area. An assessment of monthly threshold exceedance patterns shows a dynamic and changing co-exposure pattern across the year, which differs per region.
Interpretation: This work lays out a robust approach to assess simultaneous threshold exceedances of multiple environmental health risk stressors. This approach can guide policy makers in pinpointing high-risk areas particularly vulnerable to simultaneous threshold exceedances, and develop mitigation strategies for those areas.
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1. Introduction

Over the past century, the global mean earth surface air temperature has risen, leading to a notable increase in the frequency, intensity and duration of extreme heat events (IPCC. Climate Change, 2021). Consequently, populations worldwide face heightened exposure to heat, a trend projected to persist. Recently a large European-wide study found a large increase in heat-related mortality during June–August 2022 (Ballester et al., 2023). Heat stress can manifest as various heat-related diseases such as heat rash, heat cramps, heat exhaustion, and heat stroke with some cases being fatal (Kovats and Heat, 2008). Extended periods of high day and night-time temperatures can also exacerbate the detrimental effects of pre-existing respiratory and cardiovascular diseases, diabetes mellitus or renal disease (Strathearn et al., 2022).

Apart from these direct health impacts, increased temperatures influence other stressors, which in turn can induce similar adverse health effects (Fig. 1). For instance, higher temperatures and abundant sunlight expedite the reactions that form ozone (O_3), a common air pollutant. During heat waves, potential stagnant air can hinder dispersion of pollutants leading to higher concentrations (Kinney, 2018). Air pollutants, especially Particulate Matter less than 2.5 µm ($PM_{2.5}$), are major contributors to diseases such as lung cancer, chronic obstructive pulmonary disease (COPD) and stroke, making them Europe's most prominent environmental health threat (Dominski et al., 2021).

* Corresponding author.
E-mail address: Bernice.scholten@tno.nl (B. Scholten).

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Climate change also augments airborne allergenic pollen levels. Airborne pollen tend to increase during warm and dry conditions, and with higher temperatures, the flowering season starts earlier and lasts longer (Ziska et al., 2019). Additionally, the potency of certain airborne allergens can be increased via provoked chemical changes by certain air pollutants (Reinmuth-Selzle et al., 2017). Allergic reactions to airborne allergenic pollen include nasal and eye symptoms, and bronchial asthma (Fig. 1) (D'Amato et al., 2005 Sep).

Beyond the direct effect of the changing climate on the concentrations of airborne pollutants or pollen, higher temperatures can also affect the body's response upon these exposure, i.e., it is known that the absorption, distribution, metabolism and excretion of chemicals is altered upon changes in body core temperature (Leon, 2008). In addition, an increased respiration rate can result in additional exposure through inhalation (Gordon, 2003).

Despite the interconnectedness of these environmental stressors and their compounded impact on health, literature predominantly explores "isolated" exposures, overlooking the combined effects (Anenberg et al., 2020). Limited studies that encompassed all three stressors were geographically confined and only employed rudimentary heat exposure metrics (i.e., dry tropical, moist tropical, etc.) (Hebbern and Cakmak, 2015; Makra et al., 2015).

This research aims to establish a methodology for using modelled data, in conjunction with health-based threshold values, to enable an assessment of simultaneous threshold exceedances throughout Europe. More specifically, we studied hourly threshold exceedence on a 0.1° x 0.1° resolution grid (approximately 10 km x 10 km) for entire Europe, for 2021 and 2022. And lastly we investigated the monthly variation of threshold exceedance.

2. Methodology

To be able to assess simulatenous threshold exceedance of different stressors, the following steps were undertaken: i) retrieval of hourly stressor level data throughout Europe on a 0.1°x0.1° resolution grid (approximately 10 km x 10 km) for all three stressors, ii) assigning a value above which a stressor is expected to have an unacceptable negative health effect (i.e., a threshold value) for the individual stressors, and iii) determining, hourly and for every grid point, if threshold exceedance occurred in each grid for the individual stressors and for any combination of stressors. The modelled time period was from 1 January 2021 until 31 December 2022. Since we included multiple airborne allergenic pollen (birch, grass, ragweed, mugwort, olive and alder) and air pollutants (particulate matter less than 10 μm (PM_{10}), $PM_{2.5}$, nitrogen dioxide (NO_2), O_3, we defined exceedance of the threshold if any of the considered stressors in that group were at or above threshold.

2.1. Heat

The basis of the heat stress assessment is the wet bulb globe temperature (WBGT), which is one of the most commonly used indices for indicating heat stress since the 1960 s (Blazejczyk et al., 2012). This temperature takes into account the limited evaporative potential in case of high relative humidity, enhanced evaporative potential by ventilation (wind), and additional heat stress when exposed to direct sunlight. The meteorological parameters that are required to calculate the WBGT were obtained from the European Center for Medium Range Weather Forecasts (ECMWF) reanalyses. More details on ECMWF input parameters can be found in Annex I. WBGT ISO 7243 is a screening method for the assessment of the heat stress to which a person is exposed (ISO 7243, 2017). We assumed the occurrence of heat stress when the effective WBGT exceeded the recommended alert limit, which takes into account the metabolic activity, clothing types and the acclimatisation status of a person. For this we assumed an unacclimatised person, involved in light activities (i.e., a metabolic rate of 180 W) and no effects of clothing on the WBGT estimate (i.e., a clothing adjusted value of 0) (Table 1).

2.2. Air pollution

Air pollutant hourly concentrations of PM_{10}, $PM_{2.5}$, NO_2, and O_3, were simulated with the operational chemical transport model LOTOS-EUROS (Manders et al., 2017). In 2021, the WHO proposed a guideline threshold of 15 μg/m^3 for daily averaged $PM_{2.5}$ (World Health Organization, 2021). To be able to evaluate hourly pollutant exposure data, previous WHO air quality guidelines have been converted by the Dutch National Institute for Public Health and the Environment (RIVM) to hourly values based on 1) the relation between hourly maxima and

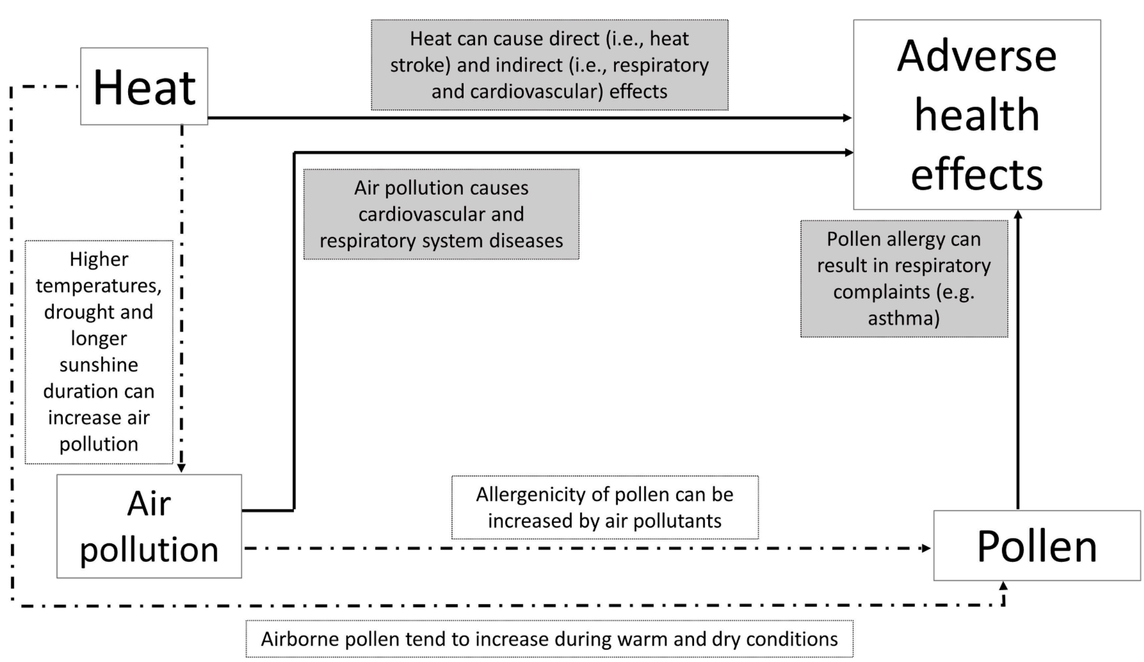

Fig. 1. Heat, air pollution and pollen impact health directly (grey boxes, solid lines) but also indirectly (white boxes, dotted lines) via interactions between environmental stressors.

Table 1
Overview of stressors and their derived hourly threshold values, as included in integrated assessment.

Stressor	Hourly threshold value	Reference
Heat (Wet Bulb Globe Temperature)	28.1 °C	(ISO 7243, 2017)
Air pollutants:		Based on (World Health Organization, 2021; WHO Regional Office for Europe, 2013)
NO_2 and O_3	60 μg/m^3	
PM_{10}	45 μg/m^3	
$PM_{2.5}$	30 μg/m^3	
Airborne allergenic pollen (birch, grass, ragweed, mugwort, olive and alder)	50 grains/m^3	Based on (Steckling-Muschack et al., 2021; Prince et al., 2018; Prince et al., 2018)

corresponding daily averages, and 2) daily mortality and daily hospital admissions in relation to air quality (WHO Regional Office for Europe, 2013). Details on the conversion are in Annex II. For $PM_{2.5}$ the ratio between the maximum hourly concentration and 24-hrs average is two, hence we multiplied the WHO threshold value for $PM_{2.5}$ with 2, resulting in an hourly limit concentration value of 30 μg/m^3. Using the mortality for all cause data (Table 2 in Annex II), whilst assuming that also daily health complaints will vary according to this ratio, the appropriate limit concentration for both NO_2 and O_3 are estimated 60 μg/m^3. For PM_{10} a factor of 1.5 is applied, as an approximation to the 66 % mass contribution of $PM_{2.5}$ to PM_{10}. Hence the threshold value for PM_{10} becomes 45 μg/m^3. If any of the air pollutant concentrations were above threshold we defined air pollution as above threshold and assumed the occurrence of air pollution stress.

2.3. Allergenic pollen

Airborne allergenic pollen considered in this work include birch, grass, ragweed, mugwort, olive and alder, for which data was retrieved from the Copernicus Atmosphere Monitoring Service. There is no commonly agreed upon threshold value for pollen concentrations that will provoke allergy symptoms (Steckling-Muschack et al., 2021). Steckling-Muschack et al. (Steckling-Muschack et al., 2021) derived a threshold value of 45 grains/m^3 based on five studies on birch pollen exposure and drug consumption. A threshold value of 22.6 grains/m^3 could be established from four studies examining ragweed pollen and the number of doctor's visits. A review by Prince et al. (Prince et al., 2018) described thresholds for ocular allergy upon grass exposure ranging from 22 to 150 grains/m^3. Levels at which patients developed mild ocular itching or nasal symptoms were at 35 grains/m^3. According to the UK Met Office, hay fever symptoms usually appear when the pollen count exceeds 50 grains particles/m^3. A reading between 50 and 150 grains/m^3 of grass pollen is considered high (Met Office, 2023). Considering all information, a threshold value for airborne allergenic pollen exposure was freely set at 50 grains/m^3 in this study, for each considered pollen separately. We defined potential pollen exposure above threshold if any of the pollen levels were above this threshold, this is considered an occurrence of pollen stress.

2.4. Analyses and software

The method described above resulted in a European-wide data set with hourly and a 0.1°x0.1° resolution grid on all stressors and their components. Using the set thresholds, hourly and spatially gridded exceedance (yes/no) of all stressors and combination of stressors were obtained. The total number of hours above threshold for an entire year (2021 and 2022), or the summerperiod of 2022 were calculated per grid cell for the three individual stressors and for combinations of the stressors. Note if there was data for all stressors at a specific time point (i.e., for all four air pollutants concentration levels are provided per grid cel) we would mark this specific grid cell as being above threshold if one or more of the four air pollutants was at or exceeding concentration levels. If all air pollutants were below the set threshold value we would mark this grid cel as not being above threshold. However if there were datamissing for any of the air pollutants, or data for those below the threshold, we would not count this grid cell in the calculation of the total hours.

The R Python language was used to process and plot the data in this study. Plots were created using the matplotlib and cartopy R Python packages. Hourly ECMWF land (CDS, 2001) and ERA-5 single layer (Hersbach et al., 2020) netcdf files for the parameters used in the WBGT calculation were downloaded from the ECMWF data store (CDS Beta) and imported using *netcdf4* (Pierce, 2023). A Python implementation of Liljegren (2008), is used for this work with the raster bricks of input meteo data.

3. Results

Simultaneous threshold exceedance to heat and one or multiple air pollutants varied strongly across Europe in 2022, with values below 1 % of the total number of hours for large parts of Northern Europe, that increase when moving in southerly direction, eventually reaching values over 8 % of the time in the Mediterranean (Fig. 2a). A similar pattern is observed for 2021 (Supplemental materials, Annex III, Figure). Values of simultaneous threshold exceedances increase to up to 25 % when considering only the warmer period of the year, i.e., May to August 2022 (Fig. 2b, Figure S2 in Annex III).

When considering all stressors, i.e., pollen data included, we observe values around 2 % threshold exceedance in Central Europe and France, with notable peaks of up to 6 % in Southern France and North Italy (Fig. 3). The maps for all stressors combined for 2021 show some regional differences, i.e., the peak of threshold exceedance in Moskow (Figure X, Annex IV).

The maps for individual stressor exposures show that for all three stressors threshold exceedance varies across Europe (Annex IV). For WBGT and airpollution, the percentages of threshold exceedances consistently (i.e., in 2021, 2022, summer period 2022) seem to increase towards Southern Europe (S5 – S10). The pollen data, however, show that pollen threshold exceedance is occurring across Europe with substantial exceedances (above 70 %) in Poland, France, parts of Rusia, Southern Norway and Northern Italy with some annual variation (Annex IV, Figure S11 and S12).

Lastly our dataset allows an evaluation of threshold exceedances throughout the year (Fig. 4). These data show, for example for Milan, monthly variation of all three stressors throughout the year. All air pollutants, but ozone, display high levels of threshold exceedances at the beginning and ending of the year, whereas ozon is above threshold levels half of the time for the period in between April and September. The WBGT threshold exceedance percentage is rising from May with a peak in July. In contrast for a more northern country such as Warsaw (Annex V, Figure S13) a different pattern is observed; for this region exposure to heat above threshold is absent but there are considerable peaks in co-exposure to various air pollutants and airborne allergenic pollen around March (ozone, PM2.5, PM10 and birch) and half of May (ozone, birch and grass). For Tirana (Annex V, Figure S14) the main period of simulatenous threshold exceedance is around July for olive pollen, ozone and high temperatures.

4. Discussion

We present an approach to calculate and visualize simulatenous threshold exceedance of heat, air pollution and airborne allergenic pollen, on a 0.1°x0.1° resolution grid (approximately 10 km x 10 km) for entire Europe. For the studied time period (2021, 2022, and the warm period of 2022 (1 May 2022—31 August), we found that threshold exceedances to all three stressors simultatenously occured in varying

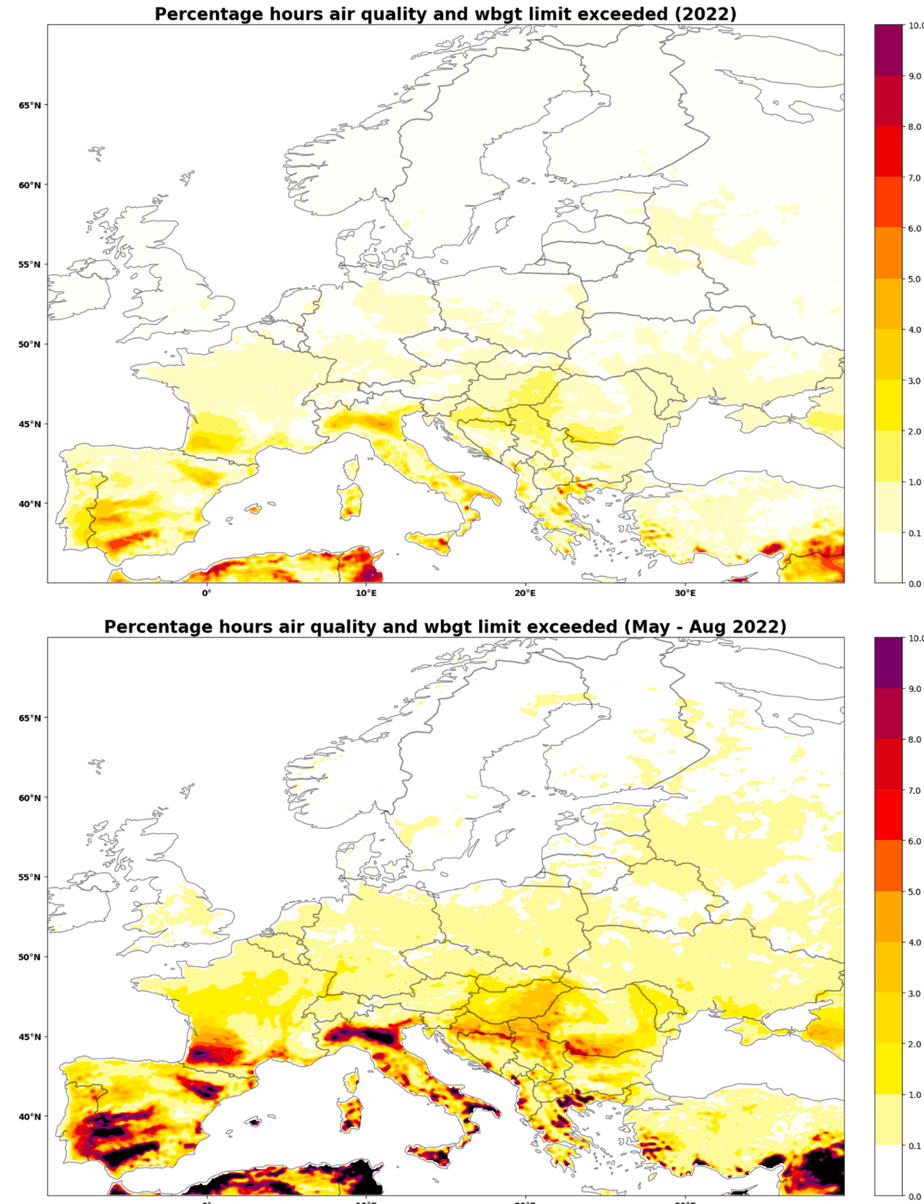

Fig. 2. Simultaneous threshold exceedance across Europe of air pollutants and heat for 2022 (Fig. 2a — figure above) and the period between 1-05-2022 and 31-08-2022 (Fig. 2b – figure below). Threshold exceedance is defined here by the hours where temperature and one or more of the air pollutants (pm10, pm2.5, NO2, O3) are simultaneously at or above threshold, and expressed as the percentage of the total number of hours of the modelled period. All percentages above 10% are colored black.

degrees throughout Europe, but most commonly in Southern European countries.

Since stress by heat, air pollution, and allergenic pollen are associated with similar adverse health outcomes, it is relevant to know where and when people might be exposed to these stressors at the same time, as simultaneous exposure might worsen the overall health outcome for individuals. This knowledge could enable policy makers to identify risk areas for vulnerable populations and develop mitigation measures focused on the identified areas with considerable co-exposures. In future research, we will forecast simulataneous threshold exceedance of multiple stressors. Short term predictions can be used as an early warning system for health officials that could be warned for potential increased hospital admissions while individuals at risk can take precautionary measures to mitigate the risk of adverse health outcomes. In general, more research is needed to understand how, and to which extent, combined exposures can affect human health. The data generated in this research can serve that purpose, for example by combining quantative co-exposure estimates with health registred databases, e.g., cardivoascular and respiratory mortality, ambulance rides or hospital admissions.

To be able to combine modelled data from different environmental risk stressors, several assumptions and conversion steps had to be made. Firstly thresholds for each individual stressor had to be determined to evaluate whether the value was above a threshold level that indicates potential adverse health effects. Since health-based regulatory levels for (different) airborne allergenic pollen are lacking, one threshold of 50 grains/m^3 was chosen for all pollen. This threshold was derived using a relative small number of patient studies combining six major pollen and various (clinical) reaction endpoints (Steckling-Muschack et al., 2021; Prince et al., 2018). Using one threshold is not accounting for possible differences in reaction doses for various pollens, however distinguishing between the different pollen could unfairly make it seem like in-depth knowledge is available. For air pollution we relied on the approach by RIVM to convert WHO air quality guidelines, which are established for comparison against 8 or 24 h average concentration, to hourly values.

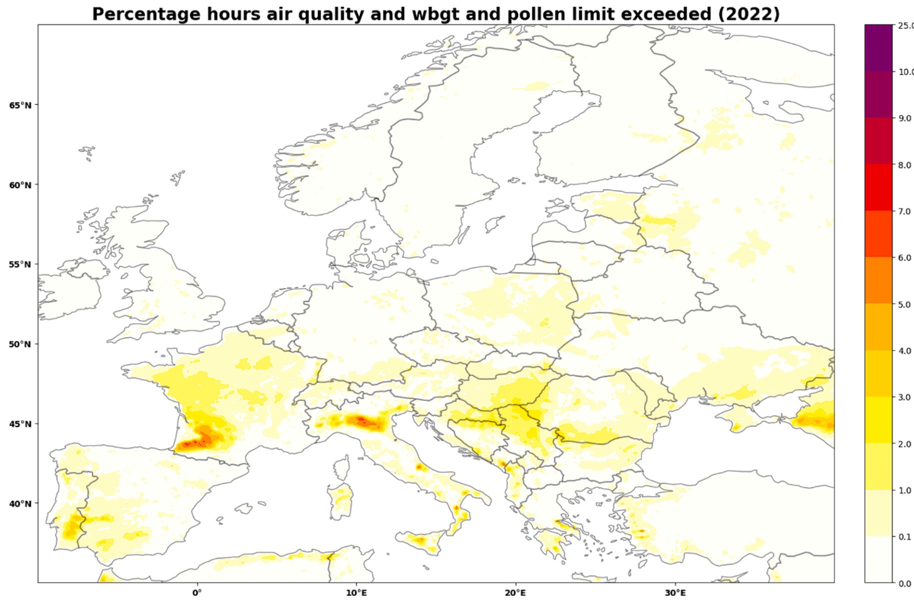

Fig. 3. Simultaneous threshold exceedance across Europe of air pollutants, heat and pollen for entire 2022. Threshold exceedance is defined as the percentage of the total number of hours of the modelled period above which temperature, and one or more of the air pollutants (pm10, pm2.5, NO2, O3), and one or more of the airborne allergenic pollen (birch, grass, ragweed, mugwort, olive and alder) is at or above threshold.

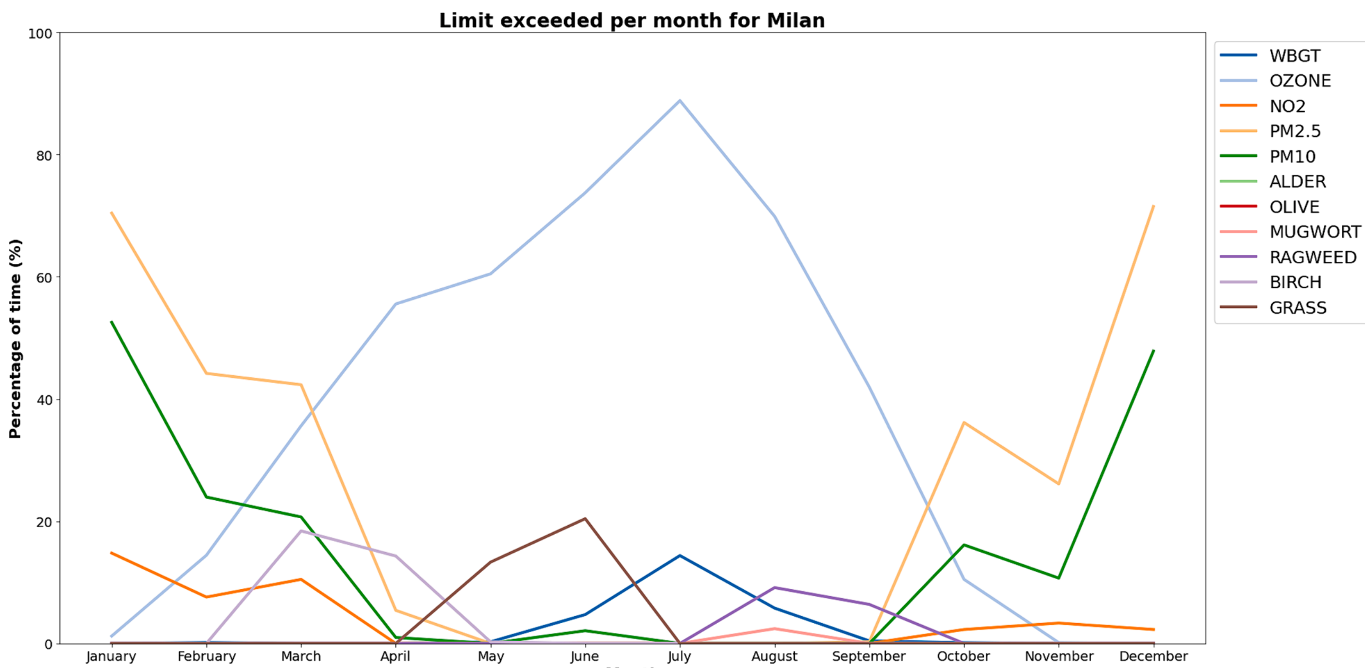

Fig. 4. Monthly threshold exceedance in Milan for the Wet Bulb Globe Temperature (WBGT), the studied air pollutants, and airborne allergenic pollen throughout the year (2022), expressed as the percentage of the total modelled period per month.

This required the assumption that the underlying dataset for longer term exposure scaled linearly with daily health complaints. For assessing heat stress we assumed the ISO7243 framework could be used to evaluate hourly heat stress levels, and that the framework was suitable for non-workers as well. Although ISO7243 refers to the extent of heat stress which can be sustained during 8 h of work, it is recommended that if the WBGT threshold is surpassed, immediate action should be undertaken. In addition, ISO7243 has been applied for non-workers. Further we assumed an unacclimatised population, which might result in an overestimation of heat stress in the (late) summer period. For all the assumptions made in this paper the same holds: upon establishment of a commonly agreed threshold or approach, our framework can be easily adopted to incorporate these changes. This also counts for the considered time period. Here we focused on 2021 and 2022, hence our findings on where and when threshold exceedance was occurring are related to this limited time period only. Our method could be extended to a period longer back, to assess potential trends over time.

We used the ISO7243 framework for assessing heat stress. The analysis were performed for an average person that is properly dressed for heat, and only performs light activity. In future efforts the framework can be adapted to represent other groups, e.g. to resemble a worker wearing full protective clothing whilst perfoming heavy labor, by adapting the metabolic rate and the clothing adjusted value. Outdoor and manual workers are known to be a particularly vulnerable group for exposure to heat and humidity because their work may involve heavy exertion, they might have less capacity to lose heat because of the need to wear personal protective clothing (Makra et al., 2015), and they may not be able to avoid direct sunlight (Romanello et al., 2021). In addition we focused on three risk stressors, but future research could extent the current approach with additional risk stressors such as occupational chemical co-exposure. A review by Bourbonnais et al. (Bourbonnais et al., 2013) identified 136 occupations with high potential simultaneous exposures to heat and chemicals, such as heavy metals, asbestos or pesticides. The absence of green spaces, another well known risk factors (Romanello et al., 2021), could be included too.

To conclude, this paper shows a unique approach to map and quantify simultaneous threshold exceedance of heat, air pollution and airborne allergenic pollen throughout Europe. This approach can guide policy makers in pinpointing high-risk areas particularly vulnerable to simultaneous threshold exceedances, and develop mitigation strategies for those areas.

CRediT authorship contribution statement

Bernice Scholten: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Koen van der Sanden:** Formal analysis. **Blaise Kelly:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Bas Henzing:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Anjoeka Pronk:** Writing – review & editing, Supervision. **W. Marty Blom:** Writing – review & editing. **Lisa Klous:** Writing – review & editing, Conceptualization. **Boris R.M. Kingma:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.109010.

References

Anenberg, S.C., Haines, S., Wang, E., Nassikas, N., Kinney, P.L., 2020. Synergistic health effects of air pollution, temperature, and pollen exposure: a systematic review of epidemiological evidence. Environ Heal 19, 1–19. https://link.springer.com/articles/10.1186/s12940-020-00681-z.

Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R.F., Pegenaute, F., Herrmann, F.R., Robine, J.M., Basagaña, X., Tonne, C., Antó, J.M., Achebak, H., 2023. Heat-related mortality in Europe during the summer of 2022. Nature Med 29 (7), 1857–1866. https://www.nature.com/articles/s41591-023-02419-z.

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., Tinz, B., 2012. Comparison of UTCI to selected thermal indices. Int J Biometeorol. 56 (3), 515–535. https://link.springer.com/article/10.1007/s00484-011-0453-2.

Bourbonnais, R., Zayed, J., Lévesque, M., Busque, M.A., Duguay, P., Truchon, G., 2013. Identification of workers exposed concomitantly to heat stress and chemicals. Ind. Health 51 (1), 25–33.

CDS. ERA5-Land Hourly Data from 2001 to Present [Internet]. 2019. Available from: https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.e2161bac?tab=overview.

D'Amato, G., Liccardi, G., D'Amato, M., Holgate, S., 2005 Sep. Environmental risk factors and allergic bronchial asthma. Clin. Exp. Allergy 35 (9), 1113–1124.

Dominski, F.H., Lorenzetti Branco, J.H., Buonanno, G., Stabile, L., Gameiro da Silva, M., Andrade, A., 2021. Effects of air pollution on health: A mapping review of systematic reviews and meta-analyses. Environ Res. 201, 111487.

Gordon, C.J., 2003. Role of environmental stress in the physiological response to chemical toxicants. Environ Res. 92 (1), 1–7. https://www.sciencedirect.com/science/article/pii/S0013935102000087.

Hebbern, C., Cakmak, S., 2015. Synoptic weather types and aeroallergens modify the effect of air pollution on hospitalisations for asthma hospitalisations in Canadian cities. Environ. Pollut. 1 (204), 9–16.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146 (730), 1999–2049.

IPCC. Climate Change 2021, The Physical Science Basis. 2021.

ISO 7243:2017. Ergonomics of the thermal Environment—Assessment of Heat Stress Using the WBGT (Wet Bulb Globe Temperature) Index. [Internet]. 2017. Available from: https://www.iso.org/standard/67188.html.

Kinney, P.L., 2018. Interactions of Climate Change, Air Pollution, and Human Health. Curr Environ Heal reports 5 (1), 179–186. https://link.springer.com/article/10.1007/s40572-018-0188-x.

Kovats, R.S., Hajat, S., 2008. Heat stress and public health: a critical review. Annu. Rev. Public Health 29 (1), 41–55. https://doi.org/10.1146/annurev.publhealth.29.020907.090843.

Leon, L.R., 2008. Thermoregulatory responses to environmental toxicants: The interaction of thermal stress and toxicant exposure. Toxicol Appl Pharmacol. 233 (1), 146–161. https://www.sciencedirect.com/science/article/pii/S0041008X08000288.

Makra, L., Puskás, J., Matyasovszky, I., Csépe, Z., Lelovics, E., Bálint, B., et al., 2015. Weather elements, chemical air pollutants and airborne pollen influencing asthma emergency room visits in Szeged, Hungary: performance of two objective weather classifications. Int J Biometeorol. 59 (9), 1269–1289. https://link.springer.com/article/10.1007/s00484-014-0938-x.

Manders, A.M., Builtjes, P.J., Curier, L., Denier van der Gon, H.A., Hendriks, C., Jonkers, S., Kranenburg, R., Kuenen, J.J., Segers, A.J., Timmermans, R.M., Visschedijk, A.J., 2017. Curriculum vitae of the LOTOS-EUROS (v2.0) chemistry transport model. Geosci Model Dev. 10 (11), 4145–4173. https://refubium.fu-berlin.de/handle/fub188/21563.

Met Office. Hay fever [Internet]. 2023 [cited 2023 Aug 13]. Available from: https://www.metoffice.gov.uk/weather/warnings-and-advice/seasonal-advice/health-wellbeing/pollen/hay-fever.

Pierce D. 'Ncdf4: Interface to Unidata NetCDF (Version 4 or Earlier) Format Data Files' [Internet]. 2023 [cited 2023 Aug 13]. Available from: https://cran.r-project.org/web/packages/ncdf4/index.html.

Prince, A., Norris, M.R., Bielory, L., 2018. Seasonal ocular allergy and pollen counts. Curr Opin Allergy Clin Immunol. 18 (5), 387–392. https://journals.lww.com/co-allergy/Fulltext/2018/10000/Seasonal_ocular_allergy_and_pollen_counts.6.aspx.

Reinmuth-Selzle, K., Kampf, C.J., Lucas, K., Lang-Yona, N., Fröhlich-Nowoisky, J., Shiraiwa, M., et al., 2017. Air Pollution and Climate Change Effects on Allergies in the Anthropocene: Abundance, Interaction, and Modification of Allergens and Adjuvants. Environ Sci Technol. 51 (8), 4119–4141. https://pubs.acs.org/doi/full/10.1021/acs.est.6b04908.

Romanello, M., McGushin, A., Di Napoli, C., Drummond, P., Hughes, N., Jamart, L., Kennard, H., Lampard, P., Rodriguez, B.S., Arnell, N., Ayeb-Karlsson, S., 2021. The 2021 report of the Lancet Countdown on health and climate change: code red for a healthy future. Lancet 398 (10311), 1619–1662. http://www.thelancet.com/article/S0140673621017876/fulltext.

Steckling-Muschack, N., Mertes, H., Mittermeier, I., Schutzmeier, P., Becker, J., Bergmann, K.C., et al., 2021 Sep 1. A systematic review of threshold values of pollen concentrations for symptoms of allergy. Aerobiologia (Bologna) 37 (3), 395–424.

Strathearn, M., Osborne, N.J., Selvey, L.A., 2022. Impact of low-intensity heat events on mortality and morbidity in regions with hot, humid summers: a scoping literature review. Int J Biometeorol 66 (5), 1013–1029. https://link.springer.com/article/10.1007/s00484-022-02243-z.

WHO Regional Office for Europe. Health risks of air pollution in Europe – HRAPIE project: Recommendations for concentration-response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide. Copenhagen; 2013.

World Health Organization. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. [Internet]. 2021. Available from: https://apps.who.int/iris/handle/10665/345329.

Ziska, L.H., Makra, L., Harry, S.K., Bruffaerts, N., Hendrickx, M., Coates, F., et al., 2019. Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis. Lancet Planet Heal. 3 (3), e124–e131. http://www.thelancet.com/article/S2542519619300154/fulltext.