ORIGINAL ARTICLE

CONTENTS

Long-term trends (compared to the pre-war period) and public health impact of surface ozone in Ukraine

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ABSTRACT

Aim: To analyze the dynamics of ambient air pollution by surface O_3 (in pre-war and wartime periods) and assess its impact on public health in order to provide proposals aimed at developing preventive programs.

Materials and Methods: Physical and chemical methods of analysis (O_3 – gas analyzers APDA-370 HORIBA, meteorological sensor WS-600); health risk assessment (AirQ+); statistical data processing methods (StatSoft STATISTICA 10.0 portable, Microsoft® Excel).

Results: Air quality monitoring in peak season 2021 and 2022 detected exceedances of the daily maximum 8-hour ozone (O_3) concentration. This resulted in a health risk for the exposed population during 70 % (174 days) and 84 % (181 days) of observations, respectively. The maximum exceedance levels were 1.7 and 2.1 times higher than the recommended limit. Estimated number of excess cases of natural and respiratory mortality in the population over 30 years due to long-term O_3 exposure: 227 (95 % CI: 0; 450) and 22 (95 % CI: 0; 54), respectively. Predictive assessments of ozone (O_3) air pollution's impact during wartime activities suggest an average increase of 40 % in additional deaths from non-communicable diseases.

Conclusions: Obtained results can serve as a basis for development of medical and environmental measures aimed at implementing adaptation proposals for public health in conditions of global climate change and wartime.

KEY WORDS: air pollution, O_3, war actions, risk assessment, mortality

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INTRODUCTION

A recent study published by the Institute for Health Metrics and Evaluation (IHME) in their "Global Burden of Disease" report identified Ukraine as one of the European countries most affected by air pollution. This pollution is estimated to contribute to 10 % of the population's social health burden, resulting in approximately 43,000 premature deaths and nearly one million lost disability-adjusted life years (DALYs) [1]. At the same time, continuous russian aggression (rocket attacks, fires in ecosystems, residential and non-residential premises, etc.) has extremely increased ambient air pollution on the territory of Ukraine [2-4]. Surface ozone (O_3) exposure is a major concern for scientists and health experts. This gas can linger in the atmosphere for extended periods and travel long distances, even across borders (transboundary) [5]. Since the photochemical processes of the O_3 formation (from precursors – nitrogen compounds, volatile organic compounds, carbon oxide, etc.) occur under the influence of solar radiation and take several hours, and the winds can carry the plume of pollution before it is formed, this makes O_3 sensitive to meteorological indicators as well (including humidity and temperature) [6, 7].

According to expert estimates, the number of population affected by O_3 concentrations, above the 2021 WHO short-term guideline value (the maximum daily eight-hour mean of 100 μg/m^3), ranged between 93 % and 98 % in the period of 2013-2020, with no downward trend over time [6]. According to epidemiological studies O_3 could cause respiratory diseases, such as chronic obstructive pulmonary disease (COPD), asthma, pneumonia and cardiovascular diseases [8-11]. In addition, O_3 can cause irritation, dryness of the skin and mucous membranes, lead to DNA damage of keratinocytes of the epidermis, thereby leading not only to a violation of their cellular function, but also to mutations, which as a result can lead to skin cancer development [12, 13].

Asian countries suffer most from global ozone-related respiratory deaths, contributing an estimated 79 % of the one million deaths worldwide. India and China alone account for a staggering number of these deaths, with approximately 400,000 and 270,000 fatalities respectively. In contrast, Africa, Europe, and North America each have reported between 50,000 and 60,000 ozone-attributable deaths, while Latin America and Oceania had fewer cases [14]. In 2020, an estimated 24,000 people in the 27 EU Member States died prematurely due to acute exposure to O_3 levels exceeding 70 μg/m^3 [15]. A study by Orru et al. (2019) and Selin et al. (2009) suggests that mortality linked to acute ozone exposure is expected to rise in Central and Southern Europe by 2050. Economic welfare losses encompassing mortality costs and leisure losses, resulting from ozone-related health impacts due to climate and precursor emission changes, could accumulate to 9.1 billion EUR between 2000 and 2050 [6].

AIM

This study aims to analyze changes in ambient air pollution caused by surface ozone (O_3) during both prewar and wartime periods. We will assess the impact of these changes on public health to develop proposals for preventive programs.

MATERIALS AND METHODS

In accordance with the assigned tasks, field studies of chemical pollution of ambient air O_3 in the surface layer of the atmosphere (SLA) were continuously conducted round the clock at air quality monitoring stations (AQMS) which are located in Kyiv city. Instrumental measurements of O_3 concentration levels were made using gas analyzers APOA-370 (Horiba), which use the method of non-dispersive ultraviolet absorption with cross-modulation (NDUV). Measurement range: 0 – 1 mln^{-1}; measurement error $\delta = \pm 1$ % [16]. Measurement of meteorological parameters (temperature, humidity and wind speed) using a meteorological sensor WS-600 with the meteorological rod of the automatic meteorological station Meteo system-Vaisala.

Measurement of mass concentration levels O_3 (one-hour and 30-minute mass concentrations) and meteorological parameters (speed, humidity and temperature indicators) was performed in the time intervals from January to December 2021-2022. This study assesses health risks associated with ambient ozone (O_3) air pollution. We compare measured O_3 concentrations to the air quality standards recommended by Ukraine's National Ambient Air Quality Standards (NAAQS) with a daily limit value of 30 μg/m^3, as well as recommendations from the World Health Organization (WHO) [17, 18]. Meanwhile, health impacts were also assessed based on the average daily maximum 8-hour ozone (O_3) concentrations during peak season. Peak season is defined as the six consecutive months with the highest running average O_3 concentration, typically from March to August [19].

The software AirQ+ v.2.2 was used to estimate the long-term health effects, in terms of mortality by using in Kyiv air quality data, city-specific relative risk (RR) values and baseline incidence [20]. The effects of O_3 on natural and respiratory mortality in the population over 30 years of age (estimated attributable proportion (AP) and estimated number of excess cases) were estimated. In this investigation, the utilization of default values for the relative risk (RR) index in the AirQ+ model was necessitated by limitations, including a lack of adequate prior studies establishing RR values specific to the target areas. These default values are derived from meta-analysis studies. In this study, RR values for the natural mortality and respiratory mortality were 1.00 (1.01–1.02) and 1.00 (1.02–1.05), respectively. Information on the number and health indicators of the exposed population was used according to the State Statistics Service of Ukraine data [21]. In addition, all absolute values of mortality were converted to 100 thousand, and the obtained results were determined with 95 % confidence interval (CI).

Statistical analyses were performed using software tools Microsoft® Excel 2019 and STATISTICA 10.0. Descriptive statistics included calculation of minimum (min), maximum (max), mean, standard deviation (SD), and standard error of the mean (SEM). Spearman's rank correlation coefficient (rs) was used to assess relationships between variables.

RESULTS

It was determined that in 2021 and 2022, the average daily mass concentrations of O_3 at AQMS ranged from (min-max): 6.5 μg/m^3 – 68.6 μg/m^3 and 5.7 μg/m^3 – 90.4 μg/m^3 (Table 1, Fig. 1). In addition, the average annual concentration of O_3 in 2021 was at the level 39.8 μg/m^3; in 2022 – 48.6 μg/m^3. The conducted studies showed an increase in the average mass concentrations of O_3 in 2022 compared to 2021 in terms of maximum values by almost 1.2 times.

Generally, number of days with an average daily O_3 concentration above 30 μg/m^3 (NAAQS) amounted to 228 (68 % of measurements) in 2021, and 241 (77 % of measurements) in 2022 [17].

Comparative analysis of interseasonal variability of O_3 pollution in the SLA showed that the highest mean values (M±m) were observed in 2021 and 2022, respectively, in (Fig. 2): spring (44.8 ± 1.2 μg/m^3 and 62.0 ± 1.2 μg/m^3) and summer periods (57.3 ± 1.3 μg/m^3 and

Table 1. Annual average 03 concentrations (µg/m3) in 2021 and 2022 (January-December)

Year	mean	median	min	max	SD	SEM
2021	39.8	38.3	3.8	80.8	17.3	0.9
2022	48.6	50.9	5.7	90.4	19.0	1.1

Table 2. Average of peak season daily maximum 8-hour means 03 concentrations (µg/m3) in 2021 and 2022

Peak season (March-August)	mean	median	min	max	SD	SEM
2021	70.28	68.82	21.36	106.38	16.497	1.25
2022	77.74	78.60	30.91	124.78	15.29	1.14

Table 3. Attributable proportion (AP) expressed as number of excess cases of mortality due to long-term 03 exposure, Kyiv (2021)

Health outcome	Estimated AP (95 % CI)	Estimated number of excess cases (95 % CI)
natural mortality	1.02 % (0 – 2.02)	227 (0 - 450)
respiratory mortality	2.02 % (0 – 4.89)	22 (0 - 54)

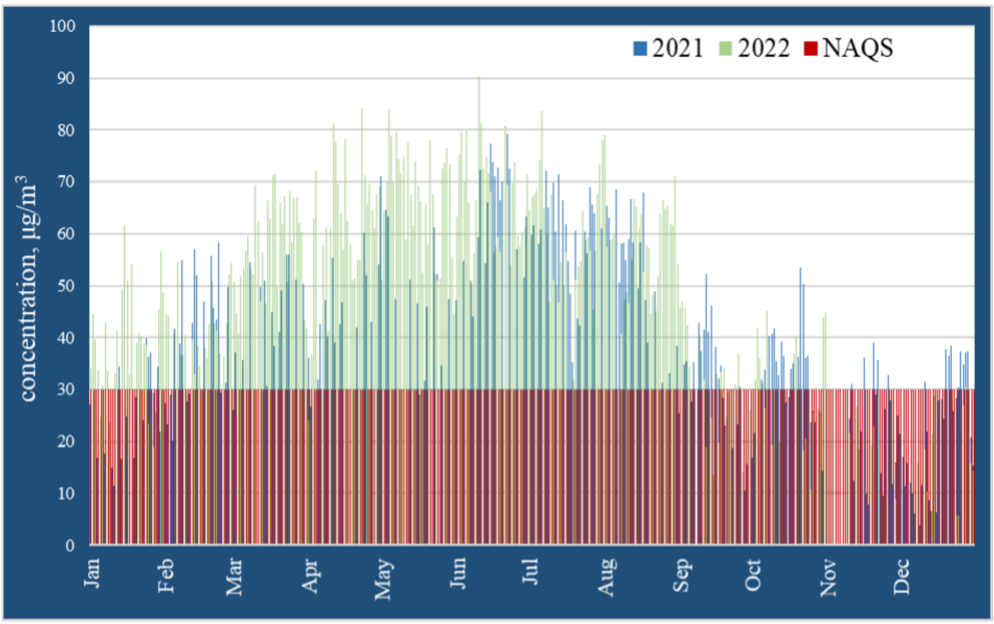

Fig. 1. Daily average 03 concentrations (µg/m3) in 2021 and 2022 (January-December). The red line corresponds to NAAQS.
*(the transfer of air masses from equatorial latitudes), as well as in June, July and the first half of August – high air temperatures (over 30 °C) [6, 22].

61.5 ± 1.1 µg/m^3); the lowest – in winter (27.6 ± 1.3 µg/m^3 and 33.7 ± 1.4 µg/m^3) and fall periods (28.2 ± 1.4 µg/m^3 and 2022 – not assessed due to lack of sufficient data (only 68 %) available due to emergency and rolling blackouts AQMS due to russian attacks on critical infrastructure), which is completely reasonable and justified for the climatic conditions of Ukraine.

In this work, was also studied the correlation between O_3 concentrations and meteorological indicators (air temperature (°C), relative humidity (%) and wind speed (m/s)). Due to non-normal data distribution, Spearman's rank correlation coefficient was employed to assess the strength of the relationship.

The findings indicate the existence in 2021 and 2022 of moderate negative correlations between O_3 and humidity (rs = - 0.59; p<0.0001; rs = - 0.68; p<0.0001, respectively), while the relationship between O_3 and temperature is found to be statistically significant and positive

(rs = 0.55; p<0.0001; rs = 0.48; p<0.0001, respectively). This, in turn, is due to the fact that an increase in humidity reduces the extinction coefficient and inhibits the flow of photochemical reactions associated with the formation of O_3, contributing to its wet deposition and increasing dry deposition (absorption by trees) [5, 22]. At the same time, an increase in O_3 concentrations during an increase in air temperature leads to a temperature inversion and acceleration of photochemical reactions of O_3 formation from precursors [5]. The Spearman correlations between O_3 and wind speed in 2021 and 2022 were of weak positive correlations (rs = 0.33; p<0.0001; rs = 0.39; p<0.0001, respectively).

Assessment of the health effects of ozone was carried out with based on an average of peak season daily max-

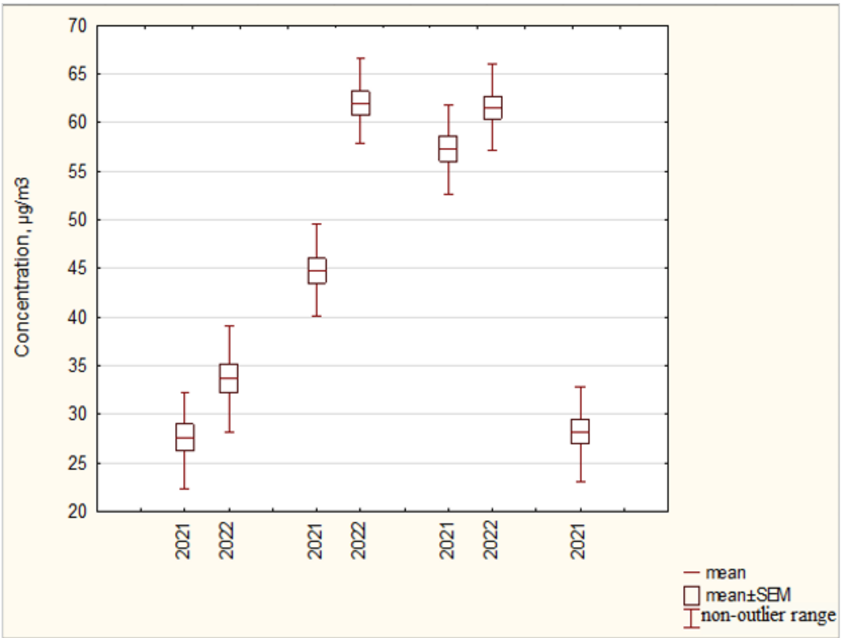

Fig. 2. Box plot daily average O3 concentrations (µg/m3) in 2021 and 2022 (different seasons).

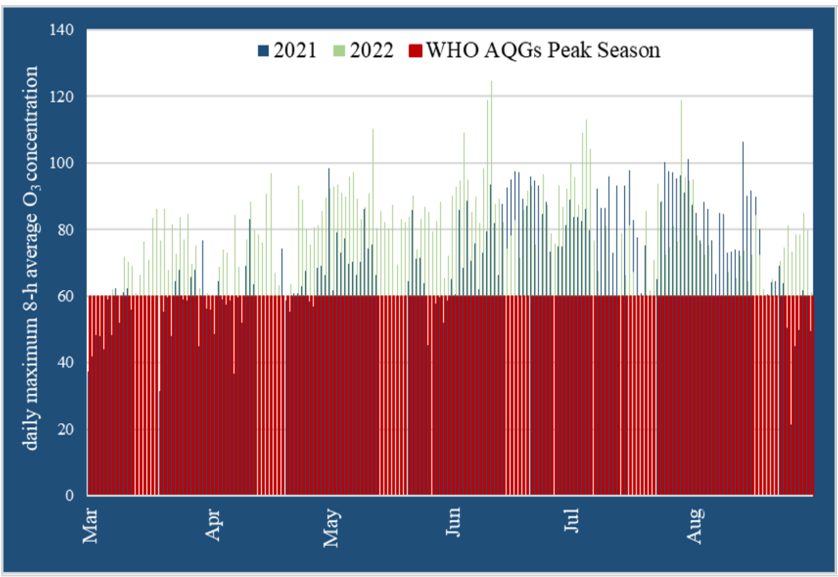

Fig. 3. Maximum daily 8-hour O3 concentrations (µg/m3) in 2021 and 2022 (March-August). The red line corresponds to the WHO limit value in peak season.

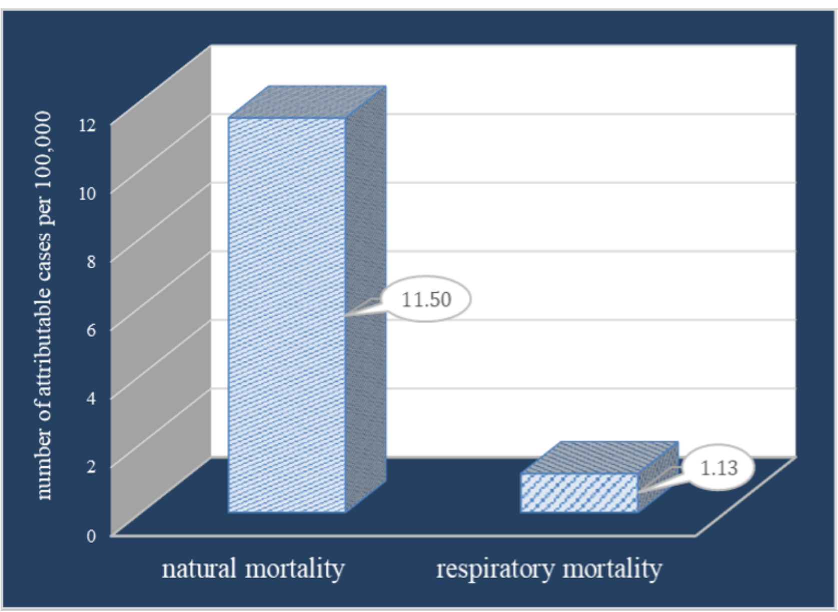

Fig. 4. Additional mortality per 100,000 population due to long-term O3 exposure, Kyiv (2021).

imum 8-hour means O_3 concentrations. For the years 2021 and 2022, the peak season mean concentrations of O_3 are shown in Table 2.

In peak season in 2021 and 2022 daily maximum 8-hour average O_3 concentrations ranged from (min-max; M±SEM): 21.36 – 106.38 μg/m^3; 70.28 ± 1.25 μg/m^3 and 30.91 – 124.78 μg/m^3; 77.74 ± 1.14 μg/m^3, respectively. Figure 3 shows the time series of the daily maximum 8-hour O_3 concentrations in 2021 and 2022 (March-August) (Fig. 3).

Air quality monitoring in peak seasons of 2021 and 2022 detected exceedances of the daily maximum 8-hour ozone (O_3) concentration set by the WHO (60.0 μg/m^3). This resulted in a health risk for the exposed population during 70 % (174 days) and 84 % (181 days) of observations, with maximum exceedances reaching 1.7 and 2.1 times the recommended level, respectively [18].

During the development and implementation of medical and environmental measures to address air pollution, quantitative assessments of its health impacts are crucial. These assessments, employing epidemiological studies, to help estimate the reduction in life expectancy and premature (additional) mortality. The AirQ+ software complex was used to estimate the long-term health effects of O_3 exposure on the population. The software considered average daily maximum 8-hour ozone concentrations during peak season (March-August) for 2021 (70.28 μg/m^3) and 2022 (77.74 μg/m^3). Due to the lack of official statistical data on the number, health indicators and mortality of Kyiv residents in 2022, quantitative risk assessments were conducted only for 2021, including a probabilistic forecast of possible consequences in the wartime period of 2022.

The health effects as described by estimated AP and estimated number of excess cases of natural and respiratory mortality in the population over 30 years of age in due to long-term exposure of O_3 is shown in Table 3.

Overall, we estimate that in 2021: 227 (95 % CI: 0; 450) and 22 (95 % CI: 0; 54) of deaths due to all (natural) causes and respiratory diseases were attributable to long-term exposure to O_3 in Kyiv, respectively.

The risk assessment also revealed an increase in the estimated number of attributable cases per 100,000 people at risk from long-term O_3 exposure in 2021. Natural causes saw an increase of 11.50 cases, and respiratory diseases increased by 1.13 cases (Fig. 4).

DISCUSSION

Ozone pollution poses a significant global threat to public health. The persistent acts of russian aggression, including rocket attacks and fires affecting ecosystems as well as residential and commercial buildings, have substantially heightened the levels of air pollution across Ukraine's territory [2-4]. O_3 formation through photochemical processes depends on solar radiation and wind movement and sensitive to humidity and temperature. Higher humidity reduces extinction coefficient, slowing O_3 formation and increasing wet deposition. Elevated temperatures accelerate photochemical reactions, converting precursors into O_3 faster. [5-7, 22, 23].

The highest peaks of maximum and average daily mass O_3 concentrations (> 30 μg/m3; Fig. 1) in 2021-2022 were recorded in April-May during the periods of the highest solar activity, which is associated with meteorological features in this period of the year in Ukraine (the transfer of air masses from equatorial latitudes), as well as in June, July and the first half of August – high air temperatures (over 30 °C) [6, 23].

Meanwhile March 2022 saw atypical surges in O_3 mass concentrations coinciding with moments of intense wartime activities. These activities, including rocket attacks, triggered widespread biomass burning, particularly wildfires, which likely caused the ozone increase; April and May saw burning of peatlands and forests in the Chernobyl Exclusion Zone, but ozone levels were almost at the same level in July, when high air temperatures (over 30 °C) were recorded on the territory of Ukraine and a more or less calm situation on the part of war-related factors [17].

Research results align with studies (Vicedo-Cabrera, A.M. et al, 2020) from 20 countries showing a 0.2 % rise in total mortality in areas with high ozone concentrations. Additionally, the APHEA2 project reported a seasonal increase in mortality: 1.13 % from respiratory diseases and 0.45 % from cardiovascular diseases during warm months [24]. Predictive assessments suggest that wartime activities likely caused higher ozone (O_3) air pollution compared to pre-war periods. Daily maximum 8-hour O_3 concentrations in 2022 reached 77.74 μg/m^3. This increase is expected to lead to an average rise of 40 % in additional deaths from non-communicable diseases. Further research is needed to confirm these findings and justify the selection of appropriate adaptation measures to protect public health during wartime conditions.

CONCLUSIONS

The highest peaks of mass concentrations of O_3 were definitely associated with meteorological features of Ukraine in certain periods of the year (transportation of air masses from equatorial latitudes) and high air temperatures (above > 30 °C). "Atypical" increases in O_3 concentrations were observed during periods of active war actions and massive rocket attacks, which led to the ignition of large areas of biomass burning (in particular, forest fires, peat bogs, etc.) and additional emissions of a large number of pollutants (precursors) that are responsible for the formation of surface O_3. This proves the fact that the conduct of active war actions on the territory of Ukraine is the reason for the increase in ground-level O_3 concentrations, and its ability to be transported over long distances across national borders, and ultimately, to climate change on a global scale.

The assessments of the effects of O_3 on public health confirms that a number of premature deaths could be prevented if O_3 levels were reduced in accordance with the values given in the WHO Air Quality Guidelines. This analysis has a number of limitations, especially related to the continuation of the military conflict and its impact on the demographic, medical, ecological and economic development of Ukraine. However, the results of this analysis provide insight into the scope and processes of how improving air quality can affect people's health, quality of life, and ultimately well-being in a wartime environment.

The obtained results can serve as a basis for the development of medical and environmental measures (in particular, implementation of preventive programs; emergency notification of the population during the unfavorable meteorological conditions; educational campaigns, etc.) aimed at implementing adaptation measures for public health in conditions of global climate change and wartime.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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