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War Impact on Air Quality in Ukraine

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Abstract: In the light of the 21st century, after two devastating world wars, humanity still has not learned to solve their conflicts through peaceful negotiations and dialogue. Armed conflicts, both international and within a single state, still cause devastation, displacement, and death all over the world. Not to mention the consequences that war has on the environment. Due to a lack of published research about war impact on modern air quality, this work studies air pollution evolution during the first months of the Russian-Ukrainian conflict. Satellite images of NO_2, CO, O_3, SO_2, and $PM_{2.5}$ over Ukrainian territory and $PM_{2.5}$ land monitoring data for Kyiv were analyzed. The results showed that NO_2 and $PM_{2.5}$ correlated the most with war activities. CO and O_3 levels increased, while SO_2 concentrations reduced four-fold as war intensified. Drastic increases in pollution (especially $PM_{2.5}$) from bombing and structural fires, raise additional health concerns, which might have serious implications for the exposed local and regional populations. This study is an invaluable proof of the impact any armed conflict has on air quality, the population, and environment.

Keywords: human conflicts; war; atmospheric emissions; air pollution

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1. Introduction

In the light of the 21st century, after going through two devastating world wars in the previous century, it might seem that humanity would finally find a way to solve their conflicts through peaceful negotiations and dialogue. Armed conflicts, both international and within a single state, still cause devastation, displacement, and death. Not to mention the consequences that war has on the natural and built environments. However, this century is not that different from others, with twenty-seven armed and six "devastating" conflicts happening in the world right now, including Afghanistan, Yemen, Ethiopia, South Sudan, Syria, and, recently, Ukraine [1]. The latter is a perfect example of how unpredictably peace can be lost anywhere on the planet. It is especially worrisome due to the involvement of nuclear power and the economic and energetic consequences that already have started to unfold, which might take this disaster to a whole new catastrophic level, and create a global outcome for many years to come.

Such drastic shifts in mass human activities must undoubtedly affect environmental quality through the changes in the anthropogenic pollution emission rates. In 2020, the scientific community was presented with an unprecedented experiment of the effects of global pandemic on modern environmental quality. Several studies analyzed the effects of the restrictions of anthropogenic (i.e., industrial, transport, etc.) activities, enforced by governments to control the spread of COVID-19, had on air quality. As expected, the findings indicated a significant reduction in concentrations of the most common (i.e., criteria) atmospheric pollutants, such as particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO and NO_2) and sulfur dioxide (SO_2) [2,3]. Meanwhile, ozone (O_3) showed some variations globally, due to its secondary formation nature. Lamentably, despite the dramatic declines in emissions of anthropogenic atmospheric pollutants, the greenhouse gas trends were not detained [4], partly due to a reduction of CO_2 ocean uptake and NO_x emissions affecting CH_4 lifetime and O_3 response [5].

A number of studies with a very different focus report that public protests or strikes also tend to significantly limit motorized transport emissions [6–9]. These exceptional events, however, may create additional sources of pollution, for instance, due to an increased use of private vehicles, or burning, and vandalism in order to create physical barriers [10–12]. Even then, an overall reduction in urban pollution levels is reported [13].

While there are various publications focusing on the impact of restrictions for normal human activities (e.g., pandemic and protests), and even the economic and psychological effects of war [14–17], there are very limited studies on war and its impact on air pollution (see Table A1, Appendix A). Some studies focus on a general understanding of the effects that war might have on air quality and global temperatures in terms of weapon development and use, as well as the economic and environmental burden of rebuilding the war-caused destruction [18–20]. Similarly, it is motivating to evaluate the environmental effects of atmospheric emissions of industrial boom after war or, in contrast, of economic crisis [21–23]. Other studies focus on the chemical composition of shells, rockets or missiles, which are pulverized during the explosion and will persist for many years in the environment (i.e., metals, etc.) continuously poisoning the environment and human health [24,25]. There are also specific case studies about the Cold War restrictions on the efforts to monitor regional and global air pollution [26], or quantitative risk assessment of premature mortality related to increased PM_{10} levels due to 1991–1992 Gulf War [27], and a consequent decrease in solar power production [28]. Finally, there are studies on regional air pollution from simultaneous destruction of major industrial sources due to industrial accidents or oil-refinery fires in Serbia [29–31]. Very few studies investigate air quality changes during a war (Table A1, Appendix A). In addition, they focus on a single pollutant, mostly PM. Moreover, to the best of our knowledge, there are no studies on the impact of recent wars on air quality. As surprising as it may be, the investigations on concentration changes of regulated atmospheric criteria pollutants during a war are nonexistent, which makes this study pioneer research of its kind.

At the same time, the fluctuations in ambient air quality levels are now a major concern, as air pollution is the world's greatest environmental threat for premature mortality [32,33]. This is especially true in cities, where almost all urban human population is breathing air quality violating the World Health Organization's (WHO) recommendations [34,35]. Atmospheric pollutants can cause a diversity of respiratory and cardiovascular health problems [36,37]. The elevated concentrations of air pollution are especially dangerous for at-risk populations: the young, the elderly, and people with compromised health [38].

Therefore, in this work, air quality evolution is assessed during the first weeks of the Russia-Ukraine conflict in a context of the business-as-usual conditions of previous years and weeks. To estimate the impact of the war on air quality in Ukraine, the war impact on concentrations of $PM_{2.5}$ (particulate matter with aerodynamic diameter $\leq$2.5 µm), NO_2, CO, O_3, and SO_2 were evaluated by comparing satellite data during periods prior to the war with data during the war. This was done considering a combination of 2-week time periods: (i) the two first weeks of the war (22 February–8 March) in 2022 vs. the same dates of 2019–2021; and then (ii) pre-war air quality (8–21 February) vs. three consecutive 2-week periods the 1–2nd (22 February–8 March), 3–4th (9–22 March) and 5–6th (23 March–6 April) weeks of war of 2022. Since the ground data for the country (except for Kyiv district) are non-existent, satellite images were used to analyze the differences between the air pollution in Ukrainian territory before and during the war. Later, PurpleAir network land data for the capital city Kyiv were analyzed to investigate local air quality dynamics over February–April 2022. While the present work does not focus on the political causes and origins of the conflict, the results of this study offer invaluable insights to the environmental impacts of war and its evolution in the biggest European country. The findings may also benefit physical and public health studies, due to a growing extended period of emission of toxic air pollution.

2. Methodology

2.1. Study Site

The independent republic of Ukraine is located in Central and Eastern Europe, in the south-eastern part of the Eastern European Plain (Figure 1a). Ukraine shares land borders with Belarus in the north, Poland in the west, Slovakia, Hungary, Romania, and Moldova in the southwest, and Russia in the east. The south of Ukraine is bathed by the Black and Azov Seas. It also has a maritime border with Romania, Russia, Bulgaria, Turkey, and Georgia. From north to south the territory of Ukraine stretches for 893 km, from west to east for 1316 km, with a total area of 603,628 km^2, occupying 5.7% of Europe and 0.44% of the world [39]. As of 1 March 2011, the total permanent population of Ukraine was 45,564,858 and 43,814,581 in 2021, showing a rapid prewar decline, with almost two thirds of population residing in urban areas [39,40].

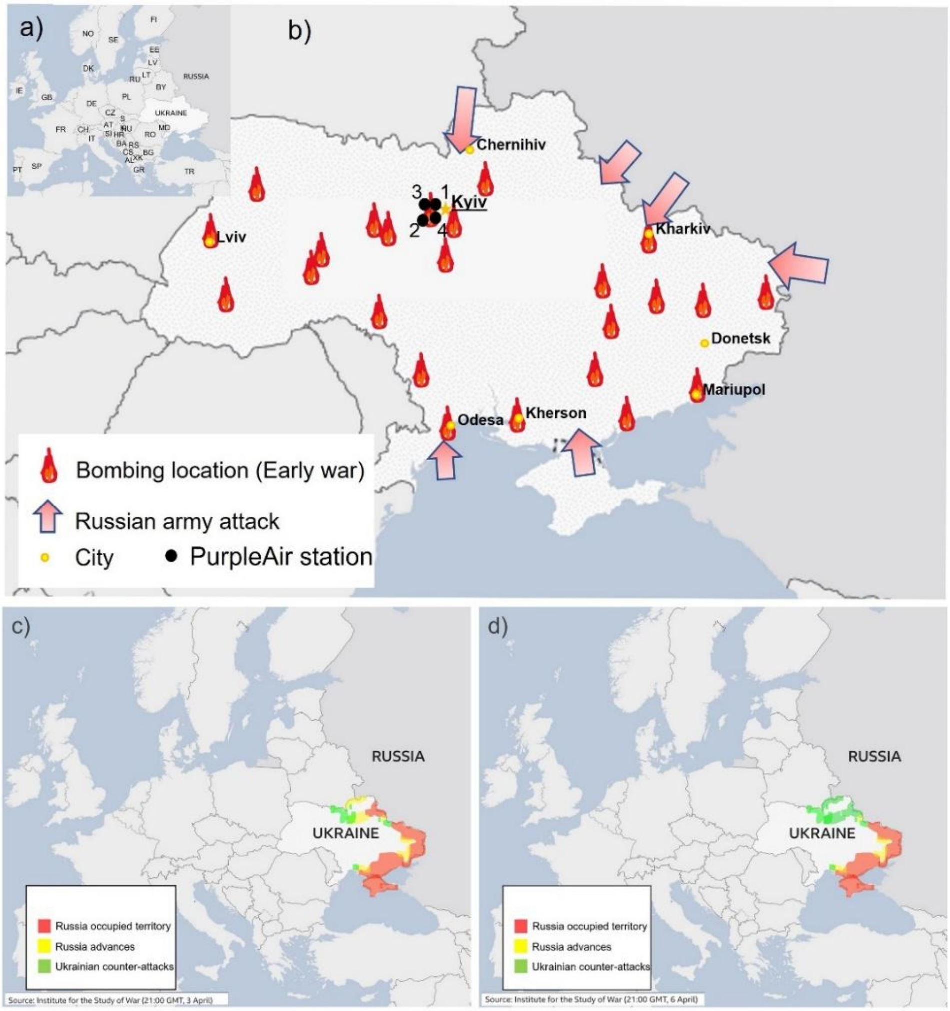

Figure 1. The territory of Ukraine (**a**) in the context of Europe; Ukrainian cities (yellow markers), attacks (flame markers) and monitoring stations (black numbered markers) (**b**); and an evolution of Russian occupation and advances and Ukrainian resistance in 3 April 2022 (**c**) and 6 April 2022 (**d**), (a breaking point in the war evolution, after which point, Russian forces focused on the occupation of eastern and southern Ukraine (at least by mid-May 2022)). Illustration adapted from the source Institute for the Study of War [41,42].

Followed by a number of armed conflict warnings and months of preparations by Russia (i.e., ~200,000 Russian troops gathering just outside the Ukrainian borders) and an issued statement by Russia's political leader on 21 February, followed by a few days (21–23 February 2022) of escalation (Figure 1b), during which Russian military forces began a "special military operation" in Ukraine on 24 February 2022 [43]. For this study, therefore, we do not consider the days before the invasion as "normal" conditions, but more likely the early days of war. The advances of the Russian army were met with a strong resistance from the Ukrainian army and civilians (Figure 1c,d) [41,42]. Due to the danger of constant bombing, shelling and shooting (i.e., thousands of civilians killed, see Figure 1b) and the destruction of water supply, electricity, and other infrastructures, in six months of conflict, according to the United Nations (UN) migration agency, an estimated 6.5–7 million people were internally displaced, and nearly 3.5–5 million people left Ukraine as war refugees [44,45]. While some people came back, there is still a large quantity of the population trying to evacuate.

According to the World Bank data and predictions, Ukraine's economy is expected to be set back by 45% due to the war and the consequent destruction of infrastructure [46]. However, the extent of economic damage might further worsen depending on the duration and intensity of the conflict. This consequently causes an extended period of emission of toxic air pollution, as towers of smoke are reported from multiple parts of the country, which might affect human and environmental health in the short- and long-term.

2.2. Satellite Data and Analysis

Since most of the on-line monitoring stations have been removed or destroyed due to war activities, the air quality assessment for the country was performed using satellite data. The concentration columns (µmol m^{-2}) of gases and particulate matter used in this research project are products of the TROPOMI instrument on board the Sentinel-precursor (S5P). This satellite carries instruments for the measurement of various pollutants such as NO_2, CO, SO_2, and O_3 [47]. In addition, concentration images (µg m^{-3}) of $PM_{2.5}$ forecast, obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), were used [10]. For our analysis, the Google Engine (GGE) platform was used [48].

Maps illustrating air pollution were produced using QGIS Madeira software version 3.4.14 [49].

The S5P satellite data resolution of concentration (mol m^{-2}) columns is 1 km^2 per pixel. Knowing that Sentinel 5P TROPOMI has some bands to identify the concentration of different pollutants, for NO_2 the "tropospheric_NO2_column_number_density" band, showing the tropospheric vertical column of NO_2, was used [50]. For CO, the band "CO_column_number_density" which refers to the vertically integrated CO column density was used [51]. For SO_2, the band "SO2_column_number_density", which means using vertical column density of SO_2 at ground level, calculated using the DOAS technique, was used [52]. For O_3, the band "O3_column_number_density" which contains total atmospheric column of O_3 between the surface and the top of atmosphere from the Royal Netherlands Meteorological Research Institute (KNMI) was used [53,54]. Finally, for the $PM_{2.5}$, medium-term weather forecasts (ECMWF) were used, specifically the particulate_matter_d_less_than_25_um_surface band that measures $PM_{2.5}$ particles with 45 km^2 resolution at the Earth's surface.

For this study, daily images were separated into two groups. The first group includes the beginning dates of the conflict in different years (2019–2022): (i) 22 February–8 March 2019; (ii) 22 February–8 March 2020; (iii) 22 February–8 March 2021; and (iv) 22 February–8 March 2022. The pollution levels for 2019 are the most representative of business-as-usual (BAU) conditions. Meanwhile, the same 2-week period in 2020 was right before the COVID-19 pandemic, thus it could also be considered as BAU conditions. The period of 22 February–8 March of 2021 was BAU affected by COVID-19 pandemic.

The second group includes a single 2-week period right before the war and three 2-week periods (6 weeks) during the war: (i) 8 February–21 February 2022; (ii) 22 February–8

March 2022; (iii) 9 March–22 March 2022; and (iv) 23 March–6 April 2022. Later, another 2-week period (weeks 7–8 of war: 7 April–24 April 2022) was added to further study $PM_{2.5}$ concentrations in the Kyiv region, as military activities around Kiev were very turbulent during the first two months of the war. Since an average image was obtained for each selected date range, raster spatial analysis tools were used to obtain the averages and one standard deviation for the study weeks. To observe the maximum values over a selected period, the average pixels with the highest values were chosen for that period in the territory of Ukraine. To calculate the above-mentioned statistics, the raw satellite pixel data were cleaned from negative <0.5 values. To calculate the above statistics, the raw satellite pixel data (NO_2, CO, O_3, and SO_2) were used for the quality indicator, which was used to select only good quality data (data > 0.5), which eliminates cloud-covered scenes, errors, and problematic retrievals [50–52,54].

The Google Earth Engine (GEE) platform was used to download L3 level products, which uses HARP commands that provide high resolution images.

To study the dynamics of air quality during the war in the region of Kiev, where the fighting was the most intense during the study period, some additional analyses were performed using Empirical Bayesian kriging (EBK). This method allows superior quantification of the uncertainty in the predictions and makes probabilistic statements at high geographical resolution of $PM_{2.5}$ or other air pollutants [55,56]. Using this method, 0.03 km^2 spatial resolution images were obtained.

Statistical analyses were performed for all criteria pollutants for the polygons of the whole Ukraine and the region of Kyiv. Sensitivity analysis was performed between different years and weeks for each criteria pollutant using statistical inference tests. A t-test was performed to compare the concentrations of air pollutants during 22 February–8 March 2022 vs. 22 February–8 March of 2019–2021. This type of analysis shows whether there are significant differences for the three pairwise comparisons: 2019 vs. 2022; 2020 vs. 2022; and 2021 vs. 2022. If p value is < 0.05, it means the difference between the data from the first two weeks of the war vs. same period of BAU years is significant. The percentage change was calculated between the 2022 and 2019–2020 (BAU). In addition, a one-way ANOVA was performed to compare the concentrations of five criteria pollutants over the 2-week periods of war. Five 2-week periods (pre-war air quality) (8–21 February 2022); the 1–2nd weeks of war (22 February–8 March 2022); the 3–4th weeks of war (9–22 March 2022); the 5–6th weeks of war (23 March–6 April 2022); the 7–8th weeks of war (7–24 April 2022) were run for $PM_{2.5}$. Total of four 2-week periods were analyzed for NO_2, CO, and O_3 (pre-war air quality (8–21 February 2022); the 1–2nd weeks of war (22 February–8 March 2022); the 3–4th weeks of war (9–22 March 2022); and the 5–6th weeks of war (23 March–6 April 2022). Finally, only three 2-week periods were analyzed for SO_2 (the 1–2nd weeks of war) (22 February–8 March 2022); the 3–4th weeks of war (9–22 March 2022); the 5–6th weeks of war (23 March–6 April 2022), due to the cloudiness obstruction on satellite images. The results of this type of statistical test show whether there are significant differences between pollutant concentrations in the region between different weeks of war. If F value is > F critical ($p < 0.05$), the difference of concentration between the weeks is considered significant.

2.3. PurpleAir $PM_{2.5}$ Data in Kyiv, Ukraine

For a study of Kyiv's regional evolution in air quality, open source available $PM_{2.5}$ land data were downloaded from PurpleAir Sensor data download tool for existing Ukrainian air quality stations at https://www.purpleair.com/sensorlist?key=DE94YTZ7Z3RM4JLQ&show=52643. This tool allows you to download PurpleAir sensor data in CSV format for selected sensors. Out of four registered PurpleAir stations (Figure 1b), all in the proximity to Kyiv (Figure 1b), only three had data for the study period (Dmitrovichi (Station 4) did not have data): Station 1 (Shepeleva) and Station 2 (Hlepcha) had complete data sets, while Station 3 (Shevchenkove) had a few days of missing data. The $PM_{2.5}$ data were downloaded for 1 February–28 April 2022, which includes the 2-week pre-war period and six weeks of war studied in this paper. The data was handled following PurpleAir sensor correction procedure established by [57], suggested for the international use [58]:

$$PM_{2.5}\text{ corrected} = 0.524 \times [\text{PurpleAirCF} = 1; \text{avgAB}] - 0.0852 \times \text{RH} + 5.72 \quad (1)$$

where, RH stands for relative humidity (%) at the station; PAcf = 1; avgAB = PurpleAir higher correction factor data averaged from the A and B channels. Each station has data for A and B channels, which were averaged and then corrected using the Equation (1). The hourly time series of $PM_{2.5}$ data were presented to show the air quality dynamics in the most intensely confronted and defended area of Ukraine in the first months of the war. To be able to compare with the satellite data, PurpleAir land data were also averaged over corresponding 2-week periods. Finally, statistical analyses of Single Factor ANOVA were done for each station to study if $PM_{2.5}$ levels were significantly different over the two weeks prewar and eight weeks of the war.

3. Results and Discussion

3.1. Air Quality during First Two Weeks of the War vs. Business-as-Usual Conditions

Satellite images of 2-week average vertical column concentrations of five criteria pollutants (NO_2, CO, O_3, SO_2, and $PM_{2.5}$) are presented in Figure 2 for 22 February–8 March of 2019, 2020, 2021, and 2022. The contrast between the first two weeks of war in 2022 compared against the same period of previous years is necessary to analyze the impact of this exceptional event on air pollution (Table 1). The pollution levels in 2019 are the most representative of business-as-usual (BAU) conditions. This 2-week period in 2020 was right before the COVID-19 pandemic, thus it could also be considered as BAU conditions. The period between 22 February–8 March of 2021 was affected by COVID-19 pandemic.

Table 1. Statistics for criteria pollutants (NO_2, CO, O_3, SO_2, and $PM_{2.5}$) in Ukraine during February 22–March 8, 2019–2022. This period shows the first two weeks of the Russia-Ukraine war of 2022 compared with the same dates of three previous years. The first value of each cell shows an average for the whole country, the next value shows one standard deviation or the spatial variability of the data, while the third value shows the maximum value for the country. Business-as-usual conditions (BAU) periods are marked with * while BAU affected by COVID-19 pandemic are marked with **. The average values for the region of Kyiv are added in bold. Percentage (%) change from BAU for Ukraine and Kyiv are added at the two last rows of the table.

	NO_2 µmol m^{-2}	**CO mmol m^{-2}**	**O_3 mmol m^{-2}**	**SO_2 mmol m^{-2}**	**$PM_{2.5}$ µg m^{-3}**
2019 *	28.4 ± 12.9/ 158.9//**39.79**	36.9 ± 1.4/46.3//**37.49**	173.7 ± 6.3/184.8//**173.55**	0.88 ± 0.71/13.69//**0.59**	5.9 ± 1.7/21.7//**5.89**
2020 *	27.2 ± 10.3/157.6//**41.82**	36.3 ± 1.2/45.5//**36.51**	164.6 ± 2.3/171.0//**164.98**	0.67 ± 0.36/12.7//**1.21**	6.1 ± 1.4/19.2//**4.72**
2021 **	23.4 ± 13.2/178.1//**36.40**	37.1 ± 1.3/42.2//**38.34**	159.5 ± 5.4/171.0//**160.80**	0.99 ± 0.87/24.1//**2.44**	7.7 ± 1.8/12.4//**4.79**
2022	21.1 ± 9.9/139.7//**24.31**	35.2 ± 1.3/36.7//**35.99**	173.3 ± 1.5/178.6//**174.98**	1.07 ± 0.98/19.3//**0.99**	3.7 ± 0.8/9.7//**3.67**
% change Ukraine	−24.10	−3.83	2.45	38.06	−38.33
% change Kyiv	−40.42	−2.73	3.38	10	−30.82

3.1.1. NO_2 during Two Weeks of War vs. Business-as-Usual Conditions

Because of the war, the concentrations of NO_2 decreased the most from all the gaseous criteria pollutants. Tropospheric column concentrations of NO_2 were significantly ($p = 0.00$) higher during BAU conditions in 2019 (28.4 ± 12.9 µmol m^{-2}, Figure 2a) and 2020 (27.2 ± 10.3 µmol m^{-2}, Figure 2b), when compared to the first two weeks of war (21.1 ± 9.9 µmol m^{-2}, Figure 2d, Table 1). In 2020, the year of COVID-19 pandemic (the sanitary emergency was established on 20 March 2020 in Ukraine), the pre-pandemic conditions' NO_2 levels were slightly lower than in 2019, except for in the Kyiv region and the Eastern territory—the most industrialized areas of the country (Table 1, Figure 2a,b). In post-pandemic year 2021 (Figure 2c, Table 1), the anthropogenic activity was reestablished (23.4 ± 13.2 μmol m^{-2}) and can be confirmed by the increased NO_2 levels in the western part of the country and around Kyiv, with peak levels of around 178 μmol m^{-2}.

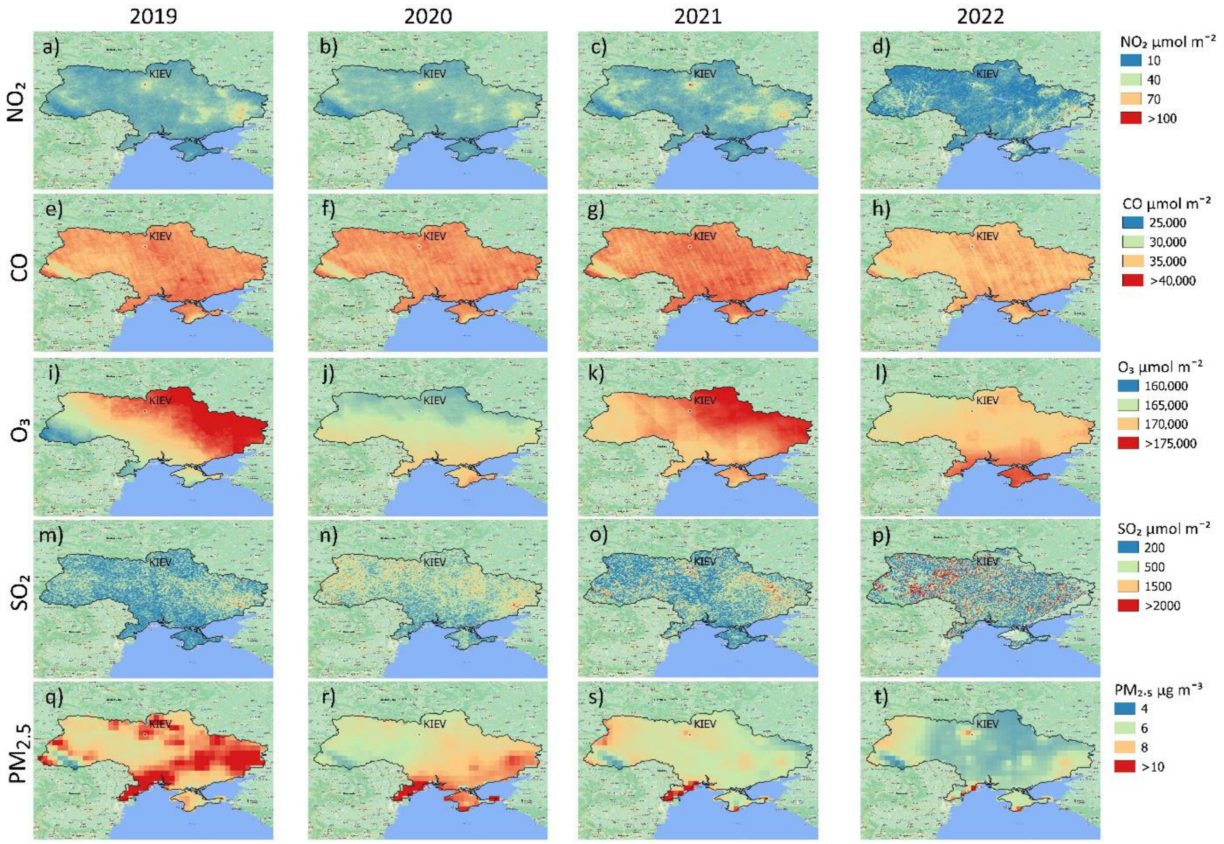

Figure 2. Concentrations of air criteria pollutants: NO_2 (**a**–**d**), CO (**e**–**h**), O_3 (**i**–**l**), SO_2 (**m**–**p**), and $PM_{2.5}$ (**q**–**t**), in Ukraine during 22 February 22–8 March periods of 2019–2022. Data averages for 2-week period of 22 February–8 March are presented by years: the first column shows 2019 (**a**,**e**,**i**,**m**,**q**), the second column shows 2020 (**b**,**f**,**j**,**n**,**r**), the third column shows 2021 (**c**,**g**,**k**,**o**,**s**) and the last (most **right**) column shows the first two weeks of war in 2022 (**d**,**h**,**l**,**p**,**t**).

The analysis of NO_2 concentrations in the Kyiv region showed that overall NO_2 concentrations were higher than over the whole of Ukraine during the 2-week periods of early spring (February 22–March 8), during all four studied years.

NO_2 levels during the first weeks of war were 24.1% lower for the whole country and 40.42% lower for the capital when compared to BAU conditions (Figure 2d, Table 1). This reduction could be attributed to the diminished anthropogenic activity during the beginning phases of the war, as previously seen in COVID-19 studies [2]. Particularly limited spikes of NO_2 can be observed in the eastern territory (max: 139.7 μmol m^{-2}), the area with the most consistently active war activity, including conflicts that started in 2014 (Figure 2d) [42]. Due to the multiple explosions and combustion processes, some scattered pollution spikes, too small in their scale to be urban emissions, show up in the context of the overall low background levels. One distinction is Crimea, where the NO_2 levels in 2022 were higher than during the previous years (Figure 2d). This is a disputed territory of Ukraine since 2014, which may be more active in terms of sustaining normal anthropogenic activity.

These findings compare well to other studies reporting NO_2 levels over urban areas [59]. Concentrations ranging around 33–116 µmol m^{-2} are normally found over remote regions, 150–200 µmol m^{-2} over cities, while concentrations over 500 µmol m^{-2} are a health concern [59,60].

3.1.2. CO during Two Weeks of War vs. Business-as-Usual Conditions

Total CO column concentrations, with sensitivity for the tropospheric boundary layer due to its longer atmospheric lifetime, demonstrate a regional pollution behavior and less variable pre-war atmospheric column levels at around 36.3 ± 1.2–37.1 ± 1.3 mmol m^{-2}, during BAU conditions (Figure 2e–h and Table 1). It can also be perceived that the concentrations of CO during the early spring (February 22–March 8) of all four studied years are higher over the region of Kyiv when compared to the whole country (Table 1).

These values also compare well to the levels in other global cities varying around 26–40 mmol m^{-2} [59]. As expected, some increase in CO levels can be noted in Kyiv and coastal areas during the "normal" year of 2019 (Figure 2e).

During the two first weeks of war in 2022 a significant (p = 0.00) but small reduction in CO levels (35.2 ± 1.3 mmol m^{-2}) can be noted for Ukraine (−3.83%) and Kyiv (−2.73%), when compared to BAU conditions in 2019 and 2020 (Figure 2h, Table 1). It is reasonable, as all combustion sources, such as motor vehicles, power stations, waste incinerators, domestic cooking, etc., emit carbon monoxide. Therefore, there must be a certain effect in CO levels due to a reduction in human circulation, and processes including industries, power production, and urban infrastructure, due to the devastating war conditions. Airstrikes and explosion combustion processes must generate CO emissions due to fires; however, it does not seem to be the case for peak levels that remain lower than usual (Table 1).

3.1.3. O_3 during Two Weeks of War vs. Business-as-Usual Conditions

The interpretations of total column of O_3 are somewhat more complicated due to its secondary nature of formation, thus making it more difficult to determine the direct impact of the war on its concentrations. It means that O_3 concentrations might increase following a drop in anthropogenic NO_x levels, which has been reported in relation to NO_x concentration drop during the COVID-19 pandemic [2,61] and ozone weekend effect [62]. NO_2 reduction was witnessed in this work as well. Consequently, in Figure 2i–l, although spatially significant (p = 0.00), small increases in O_3 levels from BAU can be observed for Ukraine (2.45%) and Kyiv (3.38%) during the first two weeks of war in 2022 (Figure 2i–l, Table 1). Concentrations of O_3 are almost always (except 2019) higher for Kyiv, when compared to the wider territory of Ukraine. However, peak O_3 levels (171.0–184.8 mmol m^{-2}) seem to have a regional influence trend, varying between the northeastern (2019 and 2021) and southern (2020 and 2022) regions of the country, and reaching its maximum peak concentration in early spring of 2019.

The total column of ozone levels varies between 40 mmol m^{-2} (tropics) and 200 mmol m^{-2} (poles), thus the concentrations reported by this study (159.5 ± 5.4–173.7 ± 6.3 mmol m^{-2}) compare well (Table 1) to the elevated levels globally reported for midlatitudes [63].

3.1.4. SO_2 during Two Weeks of War vs. Business-as-Usual Conditions

In 2021 (Figure 2o) and 2022 (Figure 2p), more areas with increased total column SO_2 levels were observed, with the average concentrations at 0.99 ± 0.87 mmol m^{-2} and 1.07 ± 0.98 mmol m^{-2}, respectively (Table 1). A trail of higher SO_2 concentrations, compared to the background levels, is seen along the most industrialized areas of the country along the Dnieper River in 2019 (Figure 2m). In 2020 (Figure 2n), a similar behavior can be observed. Meanwhile, in 2021 an overall increase in background SO_2 and clear higher levels of SO_2 in Kyiv are reported, with the highest peak levels (24.1 mmol m^{-2}) over the studied period (Table 1).

During the first 2-weeks of war in 2022 (Figure 2p), western Ukraine registered higher overall SO_2 levels than before, peaking at 19.3 mmol m^{-2} and over the whole country averaging at the maximum value of 1.07 ± 0.98 mmol m^{-2}. Over the first weeks of the war, SO_2 concentrations increased 38.06% for the whole country and 10% for the capital city, when compared to BAU conditions. In addition, Kyiv SO_2 concentrations were significantly (p = 0.00) lower during the first two weeks of war than the same period in the two previous years (Figure 2m–p). Again, as in the case of NO_2, SO_2 levels in Crimea were twice as high than in the previous years. The attacks of southern Ukraine originating from Crimea might help explain this. Similar evolution is seen in the eastern part of the country, possibly due to military activities in Donetsk and Luhansk regions and a consequent use of fossil fuels. In addition, destruction of fuel storage facilities is a common tactic reported in this war, thus further explaining an increase in SO_2 concentrations despite the reduction of "normal" anthropogenic activities.

Globally observed SO_2 total column levels range between 1 and 100 mmol m^{-2}, with levels that could jump to around 20 mmol m^{-2} over the major cities [64]. Thus, levels reported in this study compare well with previous research findings.

3.1.5. $PM_{2.5}$ during Two Weeks of War vs. Business-as-Usual Conditions

Finally, $PM_{2.5}$ demonstrated the most drastic significant (p = 0.00) reduction in the country-wide concentration average of 3.7 ± 0.8 µg m^{-3} during the first two weeks of war in 2022 when compared to BAU conditions (~6 µg m^{-3}) (Figure 2q–t, Table 1). $PM_{2.5}$ levels in the capital city were lower than in the rest of the country during every studied year, indicating fair living conditions for urban population, and suggesting other-than-mobile sources for this pollutant. $PM_{2.5}$ concentrations over the whole country dropped 38.33% and in Kyiv, decreased by 30.82%, reaching the levels under WHO's restricted health standard of 5 µg m^{-3} for annual averages (Table 1). There are, however, a few flash points around Kyiv and Donetsk, all along the borders of military actions, indicating smoke particles from localized bomb or missile destruction, which would generate fire and smoke (Figure 2t). There were over a hundred cases of explosions all over the country (Figure 1), aimed at the major cities, during the first days of the conflict [42], which might help explain the more localized pollution "hotspots", rather than regional particle pollution spread from urban areas.

3.2. Air Quality Changes during Six Weeks of War

When studying the first six weeks of the conflict and the two weeks before the war, clear changes in air quality can be seen over Ukraine (Figure 3 and Table 2). The statistical analysis showed that there is significant difference ($p < 0.05$) between all the studied periods for all the criteria pollutants indicating war dynamics impact on regional air quality.

Table 2. Statistics for criteria pollutants (NO_2, CO, O_3, SO_2, and $PM_{2.5}$) in Ukraine during the Russia-Ukraine war of 2022. Data are presented by 2-week periods: the first row shows pre-war air quality (8–21 February 2022), and the three consecutive rows show the 1–2nd (22 February–8 March 2022), 3–4th (9–22 March 2022) and 5–6th (23 March–6 April 2022) weeks of war. The first value in each cell represents an average for the whole country, the next value shows one standard deviation or the variability of the data, while the third value shows the maximum value for the country. Business-as-usual conditions (BAU) periods are marked with *. The average values for the region of Kyiv are added in bold. Percentage (%) change from BAU (i.e., two weeks before the war "w0") for Ukraine and Kyiv (in bold) are added at the end for each of three 2-week periods.

	NO_2 (µmol m^{-2})	CO (mmol m^{-2})	O_3 (mmol m^{-2})	SO_2 (mmol m^{-2})	$PM_{2.5}$ (µmol m^{-2})
w0: 8–21 February *	29.4 ± 13.7/237.3//**54.91**	35.3 ± 1.2/36.8//**36.43**	159.1 ± 1.3/161.0//**164.39**	1.6 ± 2.1/30.9//**0.90**	4.2 ± 0.8/12.2//**4.66**
w1–2: 22 February–8 March	21.1 ± 9.9/139.7//**22.52**	35.2 ± 1.3/36.7//**35.99**	173.3 ± 1.541.9/178.6//**174.98**	1.1 ± 0.9/19.3//0.98	3.7 ± 0.8/9.7//**4.75**

Table 2. *Cont.*

	NO_2 (μmol m^{-2})	CO (mmol m^{-2})	O_3 (mmol m^{-2})	SO_2 (mmol m^{-2})	$PM_{2.5}$ (μmol m^{-2})
w3–4: 9–22 March	24.2 ± 10.8/176.7//**37.68**	37.1 ± 0.9/39.1//**37.96**	171.7 ± 4.6/181.6//**169.42**	0.84 ± 0.4/11.6//**0.84**	5.2 ± 1.0/11.6//**9.47**
w5–6: 23 March–6 April	22.3 ± 7.7/93.6//**31.89**	36.8 ± 1.1/39.6//**37.55**	160.0 ± 2.0/167.3//**162.88**	0.4 ± 0.3/11.1//**0.65**	9.4 ± 1.9/24.2//**11.48**
% change w1–2 vs. w0	−28.23// **−58.98**	−0.28//**−1.21**	8.93//**6.44**	−31.25//**8.89**	−11.90//**1.93**
% change w3–4 vs. w0	−17.69// **−31.38**	5.09//**4.19**	7.92//**3.06**	−47.5//**−6.67**	23.81//**103.22**
% change w5–6 vs. w0	−24.15// **−41.92**	4.25//**3.07**	0.57//**−0.92**	−75//**−27.78**	123.81//**146.35**

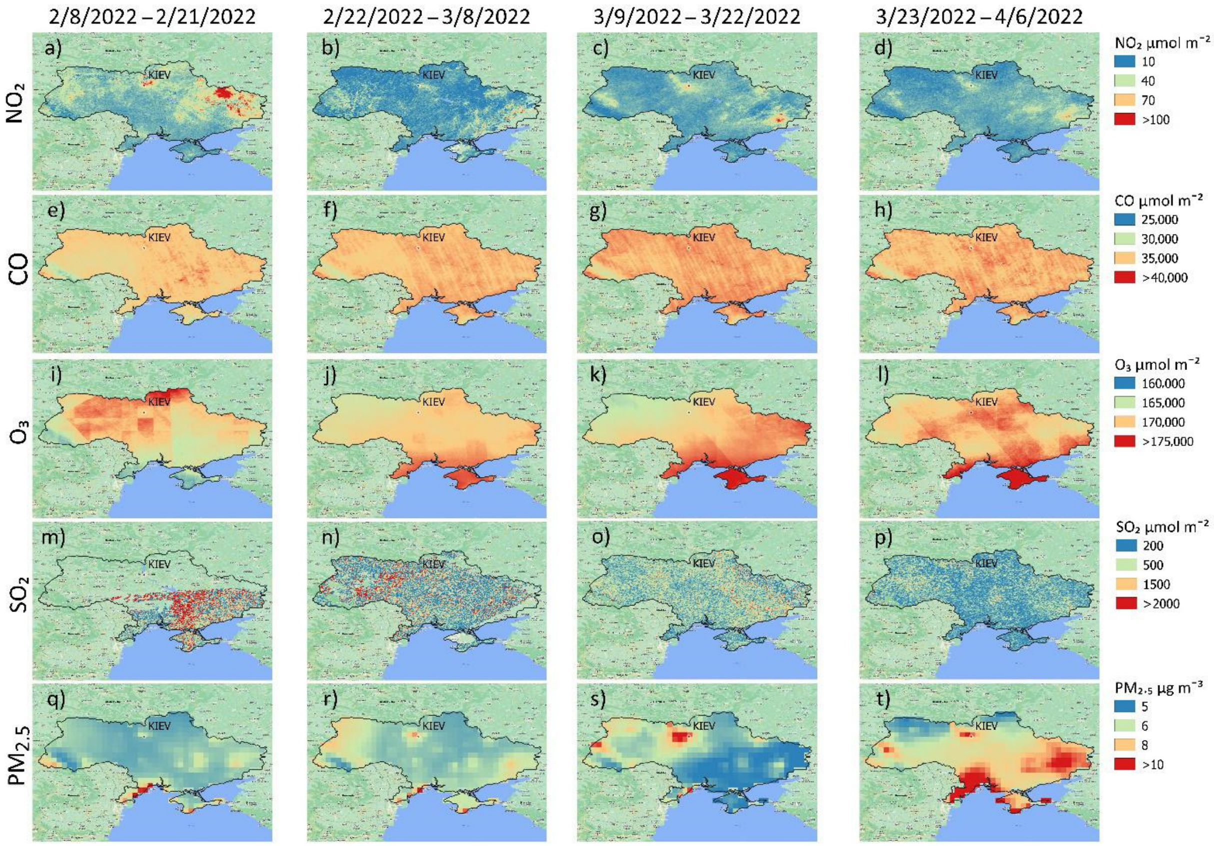

Figure 3. Evolution of concentrations of air criteria pollutants: NO_2 (**a**–**d**), CO (**e**–**h**), O_3 (**i**–**l**), SO_2 (**m**–**p**), and $PM_{2.5}$ (**q**–**t**), in Ukraine during the Russia-Ukraine war of 2022. Data averages are presented by 2-week periods: first column shows pre-war air quality (8–21 February 2022) (**a**,**e**,**i**,**m**,**q**), and three consecutive columns show the 1–2nd (22 February–8 March 2022) (**b**,**f**,**j**,**n**,**r**), 3–4th (9–22 March 2022) (**c**,**g**,**k**,**o**,**s**), and 5–6th (23 March–6 April 2022) (**d**,**h**,**l**,**p**,**t**) weeks of war.

3.2.1. NO_2 Concentration Change during Six Weeks of War

When analyzing the concentrations of NO_2 before the war started, elevated levels in the region of Kyiv and the eastern territories of the country can be observed (Figure 3a, Table 2). However, after the 22nd of February, the situation changes drastically, and since F > F critical ($p < 0.05$), the difference of NO_2 concentrations between all the weeks is considered significant. Overall levels of NO_2 drop (−28.23%) from 29.4 ± 13.7 μmol m^{-2} to 21.1 ± 9.9 μmol m^{-2} (Figure 3b, Table 2). An even larger NO_2 concentration reduction was observed for Kyiv (−58.98%). During 22 February–8 March 2022, the whole country was indicating a significant ($p < 0.05$) reduction in NO_2 pollution, which is a strong indicator of reduced anthropogenic activity, such as motorized transport, industry, etc. (Figure 3b, Table 2). This can be explained by the fact, that starting very early on, many parts of Ukraine (i.e., Lviv, Kyiv, Kharkiv, Mariupol, Kherson, etc.) received a huge number (at least a hundred) of Russian army airstrikes or shelling [42]. The situation in the streets became very dangerous, and thus people were forced to escape or hide in the underground shelters. Military attacks started from the north towards the capital, from the south, from Crimea towards Mariupol and Kherson, and from the east towards Kyiv, Mariupol, and Kharkiv (Figure 1b) [42]. During the 3–4th weeks of war in early to mid-March, Russian artillery started hitting civilian targets, as the ground advances were restricted by the Ukrainian counterattacks. This can be seen in the satellite maps of 9–22 March 2022, especially of NO_2 and $PM_{2.5}$ concentrations in Kharkiv and Mariupol (east) and Kyiv and Lviv (West) (Figure 3c,s and Table 2). During this period, although significantly ($p < 0.05$) lower than before the war, concentrations increased to 24.2 ± 10.8 μmol m^{-2} for Ukraine and to 37.89 μmol m^{-2} for Kyiv. In fact, NO_2 levels were higher in the capital during all studied weeks (Table 2). During the 5–6th weeks of war and on, heavy shelling took place in the Donbass region [42]. This can be seen in Figure 2d, where the eastern territory is the only area with increased NO_2 concentrations (Table 2). Significantly ($p < 0.05$) lower overall concentrations during the 5–6th weeks of the war point to the localization of the Russian attacks in eastern Ukraine (Figure 3d, Table 2).

While there are no studies that discuss war related NO_2 concentration change, other studies might help support these findings. For example, reduction in NO_2 concentrations were reported related to negative fluctuations in GDP in some parts of the Middle East, in the years following the Gulf War [23]. Drop in NO_2 concentrations up to ~70% was also reported in many countries during the strict quarantine phases of the COVID-19 pandemic [2]. However, probably due to the nature of public protests, including restrictions on circulation and simultaneously burning barricades or other objects, this type of study is more suitable for comparison to war conditions. NO_2 concentrations dropped 31.5–32.36% during the public protests in the Ecuadorian capital comparing the best to the findings of this study [13].

3.2.2. CO and O_3 Concentration Changes during Six Weeks of War

On the other hand, CO, O_3, and $PM_{2.5}$ show different trends. Concentrations of all these pollutants were higher in Kyiv compared to the country. An overall increase, although significant ($p < 0.05$), was very small (4.19%) for CO at 35.3 ± 1.2–37.1 ± 0.9 μmol m^{-2} by the 3–4th week of the war and (6.44%) for O_3 at 159.1 ± 1.3–173.3 ± 1.5 μmol m^{-2} by the 1–2nd week of war (Figure 3e–l and Table 2). These increases are also more regional, due to the total column concentration data, spreading over a bigger area, unlike the localized events described with NO_2 pollution. In contrast to reported CO concentration reduction, as also shown here during the first two weeks of the war for Ukraine and Kyiv, during unusual events such as global pandemic or local political protests, O_3 concentrations tend to increase, as also shown in this work due to war activities [2,13]. An increase in CO concentrations might be an indicator of an increase of war related combustion activities (e.g., fires, explosions, etc.), as opposed to the sole impact of global restrictions on human circulation.

3.2.3. SO_2 Concentration Change during Six Weeks of War

This similar behavior, demonstrated by reduction in NO_2 concentrations, was also observed for SO_2. Concentrations of SO_2 dropped significantly ($p < 0.05$) at about four times below the previous concentrations at the end of the six weeks of fighting in Ukraine, from 1.6 ± 2.1 mmol m^{-3} to 0.4 ± 0.3 mmol m^{-3} (Figure 3m-p and Table 2). The reduction in SO_2 concentrations in Kyiv is also significant ($p < 0.05$), but not as strong (−27.78%) by the 5–6th weeks of the war. In fact, the levels of SO_2 increased in Kyiv during the first two weeks of war, indicating an increase in low quality (high sulfur count) fuel combustion. This could apply to military vehicles use in the region or use of fossil fuels to survive (i.e., cooking, heating, etc.). It is further supported by the fact that before the war and until the 5th week of the war, the levels of SO_2 were always higher in the country-wide average vs. the capital.

No prior war impact studies exist which investigate SO_2 level changes during such an event; thus this study can only be compared to other types of studies, such as the COVID-19 pandemic or public protests. Sokhi and colleagues [2] showed 25–60% reduction in SO_2 concentrations, varying across the countries, depending on the level of strictness implemented nationally to stop the spread of the virus. Meanwhile, only ~7% reduction in SO_2 levels was registered during the violent public protest in Quito, Ecuador [13].

3.2.4. $PM_{2.5}$ Concentration Change during Six Weeks of War

Finally, $PM_{2.5}$ is the most interesting case pollutant when studying the impact of war dynamics on air quality. Since F > F critical ($p < 0.05$), the difference of concentrations between all the studied weeks (i.e., before and during the war) is considered significant. In addition, $PM_{2.5}$ concentrations during 3–6th weeks of the war were higher than the remaining weeks in Ukraine and Kyiv. Over the six weeks of war its concentrations almost tripled in terms of average values from 3.7 ± 0.8 μg m^{-3} to > 9.4 ± 1.9 μg for the whole country and from 4.66 to 11.48 μg m^{-3} for Kyiv (Table 2 and Figure 3r-t). Findings of this work can be partially compared to other studies, showing 1.5–3 times increase in PM_{10} levels over the duration of war due to the burning of oil fields and other military activities [27,28]. Furthermore, parts of the country at the 5–6th week of war approached peak concentrations of 24.2 μg m^{-3} (Figure 3t), which is significantly above the WHO's recommended safe levels for 24-h exposure (15 μg m^{-3}) [65]. We also note that these data represent $PM_{2.5}$ concentrations averaged over 14-day periods. Therefore, the violation of health standards for an extended period surely will cause serious short- and long-term health problems in the exposed population. This suggests that the country, as war intensified, was more regularly covered with elevated PM levels (e.g., smoke), and a massive area of the country found itself exposed to unhealthy levels of particulate air pollution.

3.3. Air Quality Monitoring Data in Kyiv

The military operation started from multiple attack points (Figure 1b). The invasion from the northern borders of the country was aimed at taking over the Ukrainian capital, Kyiv. Encountered with a huge resistance and strategic blockages of the roads (e.g., destroyed bridges, flooded territories, etc.) the military forces of Russia, in fact, never entered the capital, but halted near the eastern edges of Kyiv, where apart from intense bombing and destruction, war crimes were executed in several small towns, such as Bucha and Borodyanka (Figure 4). This war-caused significant ($p < 0.00$) air pollution intensification can be seen in the hourly data of $PM_{2.5}$ concentrations from all three available PurpleAir stations at 3–6th weeks of the war (Figure 4a,d,e, Table A2, Appendix A). This increase in $PM_{2.5}$ pollution in the region of Kyiv can also be seen in satellite maps previously analyzed for Ukraine (Section 3.2, Figure 3s,t).

$PM_{2.5}$ levels in the capital did not change much until 19–21 March 2022. During the later dates, often during night hours, peak levels climbed over 100 μg m^{-3} (Figure 4a,d) due to the intensification of the efforts to take the capital city. A 2-week average $PM_{2.5}$ concentration indicated a significant ($p < 0.05$) 46–77% increase among three monitoring stations by the 3–4th weeks of military actions when compared to pre-war normal air quality conditions (Table A2, Appendix A). These findings compare well to the findings in limited previous studies on PM_{10}. For example, during the 1991 Gulf War PM_{10} levels increased 1.5–3 times over the duration of war due to the burning of oil fields and other military activities [27,28]. By the 4–5th weeks, the Russian military was bombing civilian and military objects, including bus/train stations, hospitals, schools, theaters, etc. This resulted in 33–150% increase in $PM_{2.5}$ (Table A2, Appendix A). Once these efforts brought no fruit and the Ukrainian resistance held on the defense, the Russian army withdrew and moved towards the eastern parts of the country, showing a decline in $PM_{2.5}$ concentrations by the 7–9th weeks of war (Figure 4f, Table A2, Appendix A).

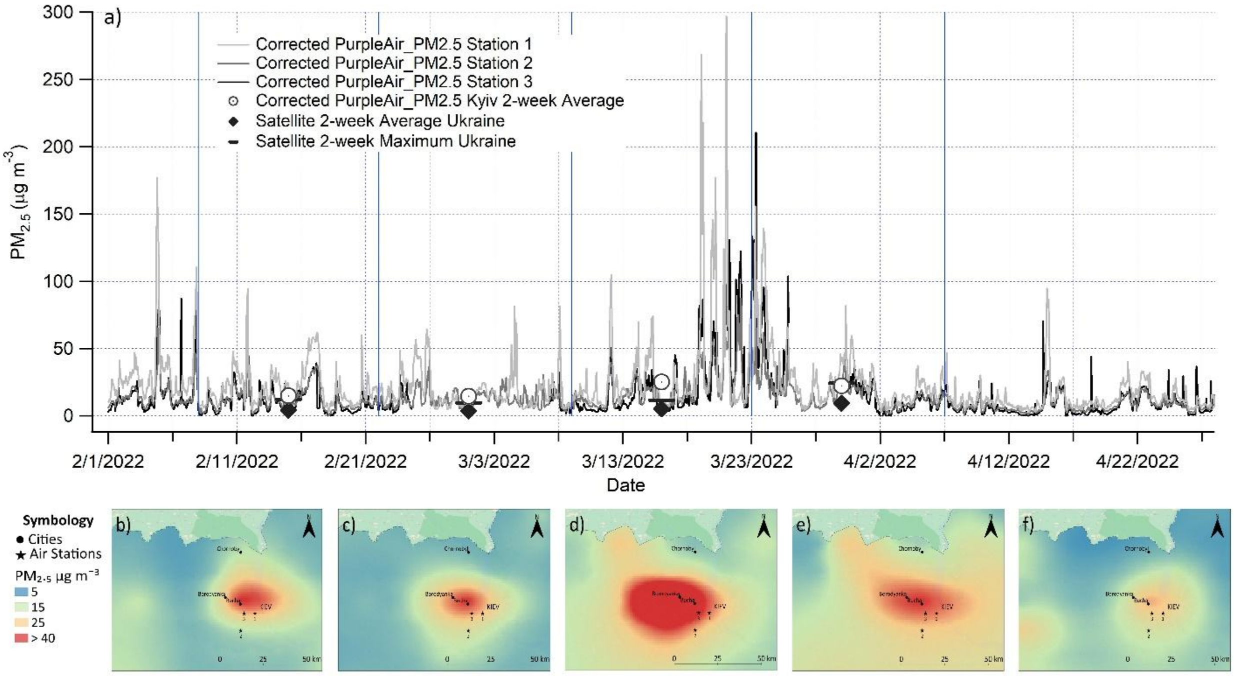

Figure 4. The upper (**a**) panel shows $PM_{2.5}$ land data for Kyiv's three functioning stations (PurpleAir), corrected hourly data (grey scale lines), and 2-week averages (grey circle markers) compared to the 2-week average satellite all-Ukraine averages (black diamond markers) and maximum values (black line markers). The 2-week periods are indicated by the blue vertical separating lines. Spatial representation of $PM_{2.5}$ satellite data for Kyiv and its surrounding territories are presented in lower panels: (**b**) pre-war air quality (8–21 February 2022); (**c**) the 1–2nd weeks of war (22 February–8 March 2022); (**d**) the 3–4th weeks of war (9–22 March 2022); (**e**) 5–6th weeks of war (23 March–6 April 2022); (**f**) 7–8th weeks of war (7–24 April 2022).

When considering war activity, even though, the probability of a nuclear disaster is always the biggest worry for humanity (i.e., Ukraine's large nuclear power system, and Russia's nuclear weapon power), there are countless other consequences to the environment and human health as a result of this invasion. Some of the impacts are short lived, while others will remain for a long time. The toxic emissions, such as heavy metals, cement, asbestos, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polychlorinated furans and dioxins, among others, originating from military activities (e.g., destruction of cities, and industrial, fuel, or acid storage facilities, etc.), will end up contaminating not only the air, but also water and soil, through wet and dry deposition [66]. There are multiple reports of governmental and civil buildings (i.e., airport, police, television or bus stations, as well as theatres, apartment buildings or private houses), factories, power plants (including Chernobyl), fuel or nitric acid storage tanks on fire and columns of smoke rising in numerous cities across the country [67]. The fact that in this work an increase in $PM_{2.5}$ levels was reported also suggests possible consequences from toxic smoke exposure. Since the use of heavy metals in weapons has increased following the WWII, every armed conflict adds large amounts of Pb and Hg [Mercury(II) fulminate] as a result of explosions [68]. In addition, Zn, Cu, Ni, Pb, and Cr are commonly utilized to coat bullets, missiles, gun barrels, and military vehicles [69,70], while Ba, Sb, and B are compounds that are used to prime weapons [71].

This study contains invaluable proof of the impacts of this war or any other armed conflict on environmental problems, specifically air pollution, implying negative health effects on the local population caught in the middle of this anthropogenic disaster. The health effects will touch not only the local population, but also the combating armies and quite possibly the surrounding countries, as shown in other studies [29–31]. While there is no way to currently examine PM chemistry, previous investigations [31] reviewed in this work suggest a huge amount of toxic chemicals affecting Ukrainian territory, which will have long-term health implications on the people and the environment.

Over two billion people were globally affected by more than 2500 disasters and 40 major conflicts since the year 2000 [72]. In the case of war, there are established guidelines regarding the protection of the natural environment in armed conflicts [72,73]. However, in an actual war, these rules are often omitted, and the responsible parties are put on trial later for their behavior during wartime. Unfortunately, the damage to the environment, infrastructure, and human health have already been done and continues to take place in Ukraine and other countries. At this point, apart from the war casualties, it is hard to estimate the actual health impact to the people of Ukraine and Russia, as confirmed by previous studies. Even years after a war, an actual impact can only be estimated with high uncertainties [27]. Therefore, the limitations of air pollution exposure to the human population are challenging due to war-disrupted public health recordkeeping. In this work, however, we present a robust estimate of air quality conditions in the country during the early, more intense, and widespread phases of the war, which will serve to later evaluate expected impacts on public health.

4. Conclusions

This study is the first of its kind to comprehensively study war's impact on modern air quality. Here, available (satellite and ground) data for five criteria pollutants (NO_2, CO, O_3, SO_2, and $PM_{2.5}$), averaged over a few different 2-week periods, were studied to help evaluate the impact of the Russia-Ukraine war on air pollution over the Ukrainian territory. Three different types of analyses were performed: (i) comparison of satellite data during the two first weeks of the war in 2022, with the same 2-week period in 2019, 2020, and 2021 for all criteria pollutants for Ukraine and Kyiv; (ii) comparison of satellite data of 2-weeks prior to the war and first six weeks (three 2-week periods) of the war for all criteria pollutants for Ukraine and Kyiv; and (iii) comparison of $PM_{2.5}$ data from three functioning PurpleAir monitoring stations in Kyiv region during two weeks before the war and eight first weeks (four 2-week periods) of the war. Statistical analyses (t-test and one-way ANOVA) showed a significant difference ($p < 0.05$) between all the studied periods for all criteria pollutants, indicating that air quality was affected by war compared to business-as-usual (BAU) conditions. And not only that, but also varied during the duration of the war covered by this study.

An overall reduction of 24.1% of NO_2 concentrations can be seen from BAU levels for Ukraine and 40.42% for Kyiv, reaching its lowest levels averaging at 21.1 ± 9.9 µmol m^{-2} in 2022 during the periods of the first two weeks of the war on 22 February–8 March. This reduction continued over to the sixth week of the war (the term of this study for the gas pollutants). The same high reduction was registered for $PM_{2.5}$ of 38.33% (Ukraine) and 30.82% (Kyiv), reaching ~3.7 µg m^{-3}, and much lower reduction for CO: −3.83% (Ukraine) and 2.73 (Kyiv) dropping to ~35.2 mmol m^{-2} nationally. This reduction can be attributed to a diminished anthropogenic activity, as many parts of Ukraine received a huge quantity of Russian airstrikes or shelling, forcing people to emigrate or hide in the underground shelters. A reduction in peak concentrations for these pollutants was also observed. The analysis of the evolution of war shows a continuous reduction in peak NO_2 concentrations; however, the average levels slightly increase on the 3–4th week of war (9–22 March 2022). This is possibly due to the intensification of airstrikes and bombing as war progressed. In contrast, overall higher O_3 (2.45% for Ukraine and 3.38% for Kyiv) and SO_2 (38.06% for Ukraine and 10% for Kyiv) levels were reported during the first two weeks of the war compared to BAU conditions. However, over the course of the war, the SO_2 levels reduced fourfold for the whole country and 27.78% for the Kyiv region, while $PM_{2.5}$ demonstrated the most drastic increase in concentrations nationally, reaching the highest levels, especially, in the Kyiv region, at 9.4 ± 1.9 µg m^{-3}. A few other hot-spots around Kyiv and Donetsk along the borders of Russian military activities suggest a prolonged exposure to smoke particle pollution from the localized bomb or missile explosions and military and civil object destruction. Parts of the country were exceeding the WHO recommended safe levels for short- and long-term exposure. Once the Russian army failed to take the Ukrainian capital, the $PM_{2.5}$ by 8th week of war the concentrations of $PM_{2.5}$ reduced in that region.

When considering war, apart from the inexcusable loss of life and massive economic losses, there are immeasurable concerns for the environment and the human health of those not involved directly in the fighting (i.e., civilians). Some of the resulting pollution impacts are short-lived, while others persist for a long time. The toxic emissions, originating from military actions and destruction, will go on contaminating not only the atmosphere, but also water and soil, through wet and dry deposition. This study, therefore, is an invaluable quantification of the impact this war or any other armed conflict has on the local population caught in the middle of this anthropogenic tragedy. The pollution-related health problems will affect not only the local population, but also the combating armies and the surrounding territories. Unfortunately, at this point, there is no way to examine the actual health impacts or the chemistry of PM pollution due to safety concerns for scientists. However, previous investigations suggest massive quantities of toxic chemicals released in Ukrainian territory, which will unquestionably have long-term regional health implications for people and the environment.

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Appendix A

Table A1. Relevant Scopus literature review for the topic of war/armed/conflict and air quality/pollution.

Year	Authors	Title	Pollutant Analyzed
1982	Hays, S.P.	From Conservation to Environment: Environmental Politics in the United States Since World War Two [21]	
1993	El-Shobokshy, M. S. & Al-Saedi, Y. G.	The impact of the gulf war on the Arabian environment—I. Particulate pollution and reduction of solar irradiance [28]	Inhalable dust particles (<15 μm) during the war
2000	Melas, D., et al.	The war in Kosovo [31]	VOCs transport during the war
2001	Vukmirović, Z.B., et al.	Regional air pollution caused by a simultaneous destruction of major industrial sources in a war zone. The case of April Serbia in 1999 [29]	Organic $PM_{2.5}$ transport during the war
2004	Vukmirovic, Z.B., et al.	Regional Air Pollution Originating from Oil-Refinery Fires under War Conditions [30]	Organic $PM_{2.5}$ transport during the war
2008	Uekoetter, F.	A twisted road to earth day: Air pollution as an issue of social movements after World War II [20]	
2008	White, R., et al.	Premature mortality in the Kingdom of Saudi Arabia associated with particulate matter air pollution from the 1991 Gulf War [27]	PM_{10} during the war
2009	Philip K. Hopke	Contemporary threats and air pollution [19]	
2012	Protopsaltis, C.	Air pollution caused by war activity [18]	
2015	Lelieveld J., at al.	Abrupt recent trend changes in atmospheric nitrogen dioxide over the Middle East [23]	NO_2 after the war
2016	Rothschild, R.	Détente from the air: Monitoring air pollution during the cold war [26]	
2019	Brimblecombe, P.	War and Urban-Industrial Air Pollution in the UK and the US [22]	
2021	Hadei, M., et al.	A systematic review and meta-analysis of human biomonitoring studies on exposure to environmental pollutants in Iran [24]	

Table A2. Anova single factor analysis for three available ground-level monitoring stations for $PM_{2.5}$: Station 1 (Shepeleva); Station 2 (Hlepcha); and Station 3 (Shevchenko). w0 is 2–21 February 2022; w1 is 22 February–8 March 2022; w3 is 9–22 March 2022; w4 is 23 March–6 April 2022.

ANOVA: Single Factor for Station 1—Shepeleva					
SUMMARY					
Groups	Count	Sum	Average	Variance	
w0_S1_SHEPELEVA	336	7256.665	21.59722	204.9428	
w1_S1_SHEPELEVA	336	6202.095	18.45862	164.4583	%increase
w2_S1_SHEPELEVA	336	10,599.05	31.5448	1778.533	46.05956
w3_S1_SHEPELEVA	336	9662.835	28.75844	620.4203	33.15806
w4_S1_SHEPELEVA	336	4625.559	13.76654	139.8192	

Table A2. *Cont.*

ANOVA: Single Factor for Station 1—Shepeleva						
SUMMARY						
ANOVA						
Source of Variation	SS	df	MS	F	p-value	F crit
Between Groups	71,859.98	4	17964.99	30.88708	7.63×10^{-25}	2.37724
Within Groups	974,238	1675	581.6346			
Total	1,046,098	1679				
ANOVA: Single Factor for Station 2—Hlepcha						
SUMMARY						
Groups	Count	Sum	Average	Variance		
w0_S2_HLEPCHA	336	3962.496	11.79314	63.14862		
w1_S2_HLEPCHA	336	4186.886	12.46097	34.1438	%increase	
w2_S2_HLEPCHA	336	6260.402	18.63215	201.3436	57.99139	
w3_S2_HLEPCHA	336	5951.278	17.71214	191.8918	50.19016	
w4_S2_HLEPCHA	336	2700.069	8.03592	32.85577		
ANOVA						
Source of Variation	SS	df	MS	F	p-value	F crit
Between Groups	26,098.07	4	6524.519	62.33017	3.71×10^{-49}	2.37724
Within Groups	175,333.5	1675	104.6767			
Total	201,431.6	1679				
ANOVA: Single Factor for Station 3—Shevchenko						
SUMMARY						
Groups	Count	Sum	Average	Variance		
w0_S3_SHEVCH	336	3767.275	11.21213	96.98908		
w1_S3_SHEVCH	80	905.5812	11.31976	48.45489	%increase	
w2_S3_SHEVCH	336	6683.625	19.89174	523.326	77.41274	
w3_S3_SHEVCH	223	6242.833	27.99477	1182.927	149.6829	
w4_S3_SHEVCH	336	2462.478	7.328803	62.97594		
ANOVA						
Source of Variation	SS	df	MS	F	p-value	F crit
Between Groups	71,253.89	4	17813.47	46.96649	6.38×10^{-37}	2.378743
Within Groups	495,340.3	1306	379.2805			
Total	566,594.2	1310				

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