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Remote sensing through the fog of war: Infrastructure damage and environmental change during the Russian-Ukrainian conflict revealed by open-access data

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ABSTRACT

The Russian-Ukrainian conflict spawned a high-intensity war that shattered decades of peace in Europe. The use of drones and social media elevates open-source intelligence as a critical strategic asset. However, information from these sources is sporadic, difficult to confirm, and prone to manipulation. Here, we use open-access spaceborne remote sensing data to probe the damage to infrastructure on and off the frontline at the city, region, and country-wide scales in Ukraine. Nighttime light data and Synthetic Aperture Radar images reveal widespread blackout and unveil the destruction of battleground cities, offering contrasted perspectives on the impact of the conflict. Optical satellite images capture extensive flooding along the Dnipro River in the aftermath of the breach of the Kakhovka dam. Leveraging visible, near-infrared, and microwave satellite data, we bring to light disruption of human activities, havoc in the environment, and the annihilation of entire cities during the protracted conflict. Open-source remote sensing can offer objective information about the nature and extent of devastation during military conflicts.

1. Introduction

The Russian full-scale military invasion of Ukraine on February 24, 2022, started a high-intensity war at the doorsteps of Europe, breaking decades of peaceful international relations in the Western world, threatening global food security, and stressing an already fragilized world economy [Behnassi and El Haiba, 2022; Ben Hassen and El Bilali, 2022; Guenette et al., 2022; Gaio et al., 2022]. Within months, Russian troops secured the newly occupied territories of Luhansk, Donetsk, Zaporizhia, and Kherson, while Crimea had been annexed since 2014. After a successful Ukrainian counter-attack that finally reclaimed territories north of Kyiv and east of Kharkiv to Kupiansk and the right bank of the Dnepro River in November 2022, the conflict turned into a trench war reminiscent of World War II, claiming tens of thousands of lives on both sides. The outcome of the ongoing second Ukrainian counter-attack that started in early June 2023 is still undetermined.

The Russian-Ukrainian war is the first high-intensity military conflict to take place in the twenty-first century, in the age of social media. For the first time, real-time information from the frontline becomes available on platforms like Facebook, X (formally known as Twitter), and Tiktok, directly shared by belligerents from both sides. Drones have been widely adopted as new military technology in the theater of war, providing images of military operations that help ascertain the progression of troops and losses. The abundance of publicly available information from the frontlines has turned open-source intelligence (OSINT) into a strategic military asset and another tool for the war of communication [Hauter, 2023]. The military map shown in Fig. 1 with the position of Russian defense lines, location of important military targets, and timeline of occupied territories, is entirely obtained from open sources (see Data Availability Statement). However, such information is sparsely distributed and subject to manipulation for propaganda [Alyukov, 2022a, b]. Independent means of assessing war developments are necessary.

Remote sensing has become a powerful tool to assess military situations and monitor conflicts on and off the frontline. Monitoring of explosions using a dense local seismological network provided near real-time information about bombardments and firing of ordnance in a radius of 400 km throughout the Zhytomyr, Kyiv, and Chernihiv provinces in northern Ukraine during the first few months of the war [Dando et al., 2023]. Spaceborne remote sensing has proven useful to assess devastation caused by sudden natural disasters, such as earthquakes, volcanic eruptions, and floods in remote locations [Elliott et al., 2016; Wang et al., 2018; Munawar et al., 2022; Barbot et al., 2023]. However, monitoring such high-intensity battles across a large country for extended periods remains challenging [Li et al., 2013; Washaya et al., 2018]. Previous studies of nighttime-light [Huang et al., 2023; Li et al., 2022], building damage [Aimaiti et al., 2022], and land-cover changes

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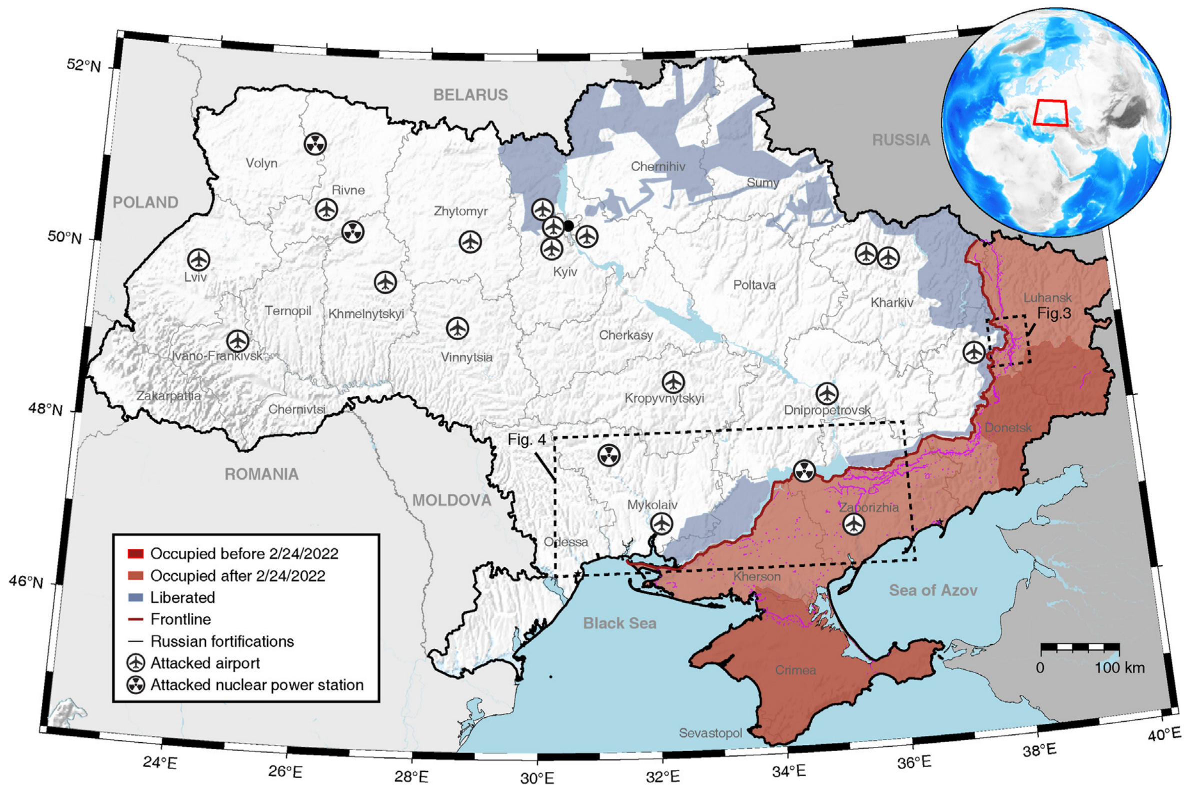

Fig. 1. Situation of the Russian-Ukrainian war as of September 2023. The map shows the distribution of liberated (blue) and occupied (red) territories, missile strikes on civilian infrastructure (airports and nuclear power stations), frontline (red line), and Russian lines of defense (purple line) from open-source intelligence (OSINT).

[Ma et al., 2022; Shevchuk and Vyshnevskyi, 2022] demonstrate the multi-faceted impacts of the war in Ukraine. Tracking the footprint of the conflict on human activity, human infrastructure, and the environment requires data assimilation from various sensors with different spatial and temporal scales.

In this study, we harness open-access spaceborne remote sensing data to assess the extensive damage inflicted upon civilian infrastructure both on and off the frontline in Ukraine. We examine the country, region, and city scales to gain a comprehensive understanding of the devastating impact of the long-lasting conflict. Leveraging visible and near-infrared images from the Suomi satellite [Bennett and Smith, 2017], synthetic aperture radar images from the Sentinel-1 satellite [Butler, 2014], and optical images from the Sentinel-2 [Butler, 2014] and Landsat [Woodcock et al., 2008] satellites, we build proxies for disturbance in human activities, ravages in the environment, and the obliteration of entire cities.

2. Spaceborne remote sensing for conflict monitoring

We describe the use of open-source remote-sensing data to monitor the Russian-Ukrainian war at different spatiotemporal scales. Spaceborne sensors record electromagnetic waves radiated or reflected from Earth's surface with wavelengths ranging from hundreds of nanometers to tens of centimeters, enabling semi-continuous change monitoring on a global scale, impervious to political boundaries and natural obstacles. Although the visible wavelengths facilitate the interpretation of satellite daytime acquisitions, they remain affected by clouds and other particulates. Other wavelengths of electromagnetic waves, such as microwaves, enable nighttime acquisitions through clouds but require more involved, dedicated processing [e.g., Yun et al., 2015; Washaya et al., 2018]. Here, we process and analyze remote sensing data in the near-infrared, visible, and microwave ranges to capture some of the multifaceted impacts of the Russian-Ukraine war.

We use a comprehensive methodology to integrate various open-access spaceborne remote sensing data and unveil the infrastructure damage caused by the Russian-Ukrainian conflict at different spatial and temporal scales. First, we use the nightlight data from Visible Infrared Imaging Radiometer Suite (VIIRS) to capture alterations in human activities, especially in conflict-affected areas. This provides a holistic perspective on the impact of war on human activities and illuminates how nightlight change during the conflict. Then, we use Synthetic Aperture Radar (SAR) data from the Sentinel-1 satellite to track battles and the destruction of two representative regions, capturing the evolution of destruction during the war and providing insights into the dynamics of urban warfare. Finally, we employ optical satellite images from Sentinel-2 and Landsat to assess large-scale changes in the natural environment resulting from the conflict. The integration of these diverse datasets facilitates a comprehensive and reliable analysis of the on-going war from different perspectives, encompassing shifts in human activity, the leveling of cities, and the environmental toll. This approach overcomes the challenges posed by the sporadic, difficult-to-confirm, and often-manipulated information found in traditional open-source intelligence and modern social media platforms during times of conflict.

2.1. Near-visible and visible nightlight

We first consider large-scale images of Eastern Europe that document the change in human activity at night. We process time-series of images acquired by the Visible Infrared Imaging Radiometer Suite (VIIRS) carried by the Suomi satellite maintained by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) [Bennett and Smith, 2017] for the level of nighttime light in Ukraine. In urban environments, the sensor is most sensitive to artificial lights, providing a proxy for changes in human activity [Levin et al., 2020; Huang et al., 2023].

We compare monthly averaged nightlight images taken before and after February 2022, which marks the onset of the Russian invasion (Fig. 2). In nearby countries not directly affected by the war, such as

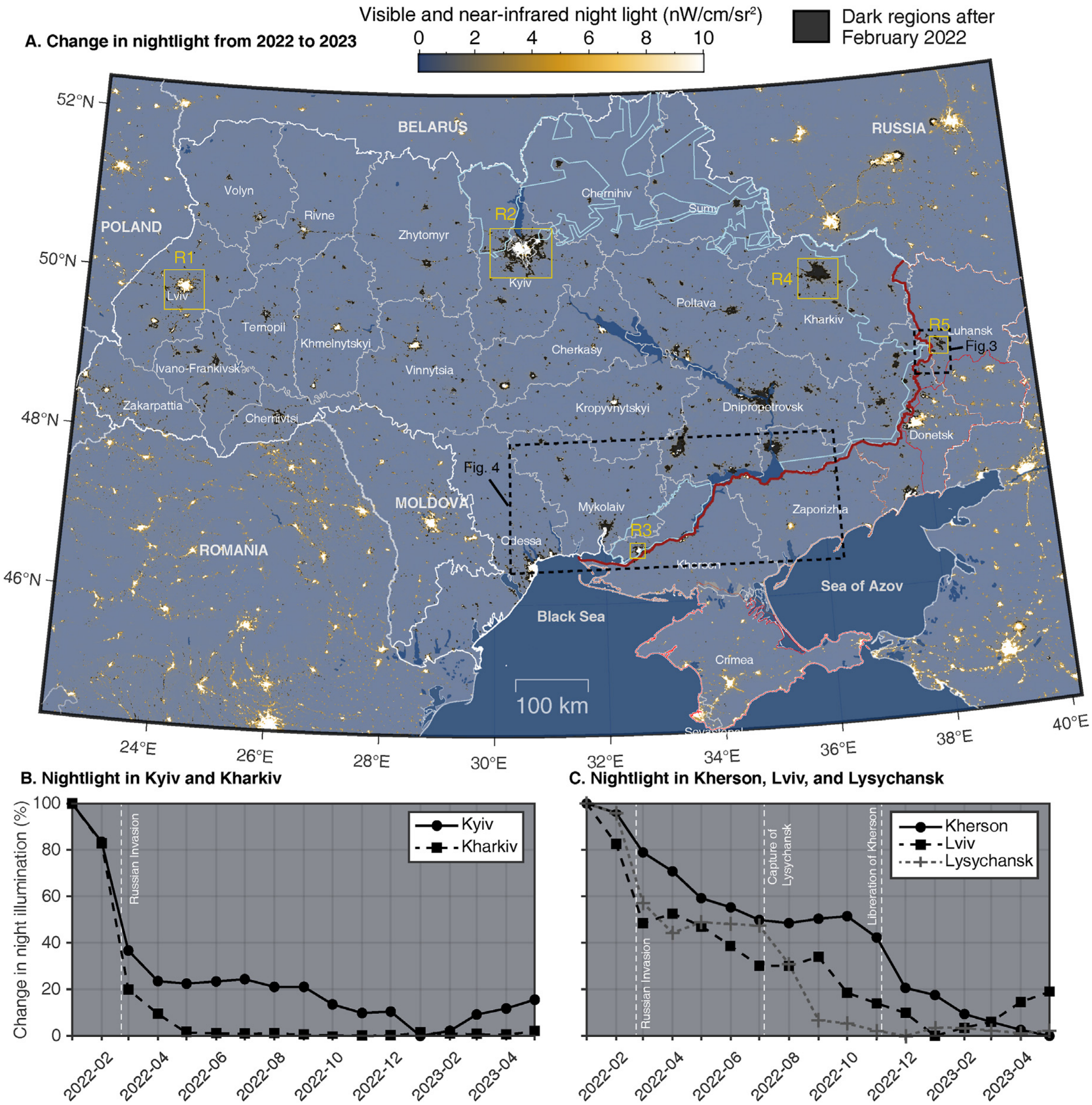

Fig. 2. Dark nights in Ukraine. a) Change in nightlight detected in the near-infrared and visible wavelengths by the Visible Infrared Imaging Radiometer Suite (VIIRS) over Ukraine and neighboring countries from January 2022 to January 2023 (background color). The sensor is mostly sensitive to artificial lights in large agglomerations. The regions that turned dark after the Russian invasion are masked in black. R1-R5 marked with yellow rectangles are five selected regions for further analysis, namely Lviv, Kyiv, Kherson, Kharkiv, and Lysychansk. b) Evolution of nightlight over Kiyv (R2) and Kharkiv (R4) with a sudden drop after the Russian invasion. c) Evolution of nightlight of Kherson (R3), Lviv (R1), and Lysychansk (R5) with additional changes after the capture of Lysychansk and the liberation of Kherson. The reduction of nightlight over most of the free Ukrainian territories highlights a major change in human activity.

Moldova, Romania, and Poland, the spatial distribution and intensity of nightlight are stable, indicating the continuation of the previous way of life. In contrast, much of Ukraine is now dark at night, indicating a major shift in circumstances. Across all of free Ukraine, innumerable cities now appear invisible at night. Only about a dozen large cities, such as Lviv and Khmelnytskyi in the west and Vinnytsia, Kyiv, and Cherkasy in Central and Eastern Ukraine continue to exhibit some nightlight downtown. Some large agglomerations in Eastern Ukraine, such as Kharkiv, Dnipro (formerly Dnipropetrovsk), Zaporizhzhia, and Mykolaiv, are virtually blacked out.

We explain these observations by blackout regulations that mitigate frequent bombardment of civilian infrastructures by Russian long-range missiles, curfews that limit car traffic at night, and the exodus of a significant part of the population to friendly countries at the onset of the war. Remarkably, the occupied regions of Ukraine do not follow the same pattern, with Luhansk, Donetsk, Melitopol, and Simferopol and Sebastopol in Crimea showing undisrupted nightlight. Indeed, Crimea continues to strive as a Russian tourist destination, almost oblivious to the nearby tragedy. The contrasting behavior betrays the different conducts of the Russian and Ukrainian armies, with no illegal bombardment of civilian infrastructures in occupied Ukraine.

Nightlights indicate various changes in human activities across Ukraine. For example, while Kyiv and Kharkiv durably blacked out shortly after the Russian invasion (Fig. 2b), Lviv underwent a series of gradual steps toward blackout due to frequent bombardment by Russia of its electric power grid (Fig. 2c). A second drastic black-out in Lysychansk followed its capture by Russian forces. In contrast, the second drop of illumination in Kherson corresponds with its liberation by Ukrainian forces on November 9, 2022 (Fig. 2c).

2.2. Microwave spectrum

SAR is a form of active-source remote sensing operating in the microwave spectrum with wavelengths from 1 mm to 30 cm that are not impeded by cloud cover or any lack of illumination, regardless of weather and environmental conditions. Repeat-pass interferometry provides a sensitive measure of the coherence of ground scatterers, being irremediably degraded when damage occurs. SAR interferometry has already proven an invaluable tool to monitor widespread damage caused by natural disasters when affected areas are otherwise inaccessible [Plank, 2014; Yun et al., 2015; Washaya et al., 2018]. The Sentinel-1 SAR satellites, operate in C-band with a wavelength of $\sim$ 5.6 cm with a spatial resolution of $\sim$ 20 m over a swath of $\sim$ 410 km, providing freely accessible SAR acquisitions via ESA's datahub. The footprint and spatial resolution of Sentinel-1 SAR acquisitions are ideal for monitoring urban warfare with up to 12-day updates at the city scale.

We process Sentinel-1 SAR images to obtain time-series of coherence maps of the battles of Rubizhne, Severodonetsk, and Lysychansk that unfolded from March to July of 2022, and the year-long battle of Bakhmut from May 2022 to May 2023. We coregister SAR images relative to a common scene and compute coherence maps 12 and 24 days apart starting at the beginning of 2021 (Fig. S3). We flag highly damaged areas by comparing the SAR coherence before and after the war (Method, Figs. S4 and S5). Although native SAR resolution is sufficient to resolve individual buildings, the raw images suffer from speckle, a form of multiplicative noise from the scattering of electromagnetic waves within

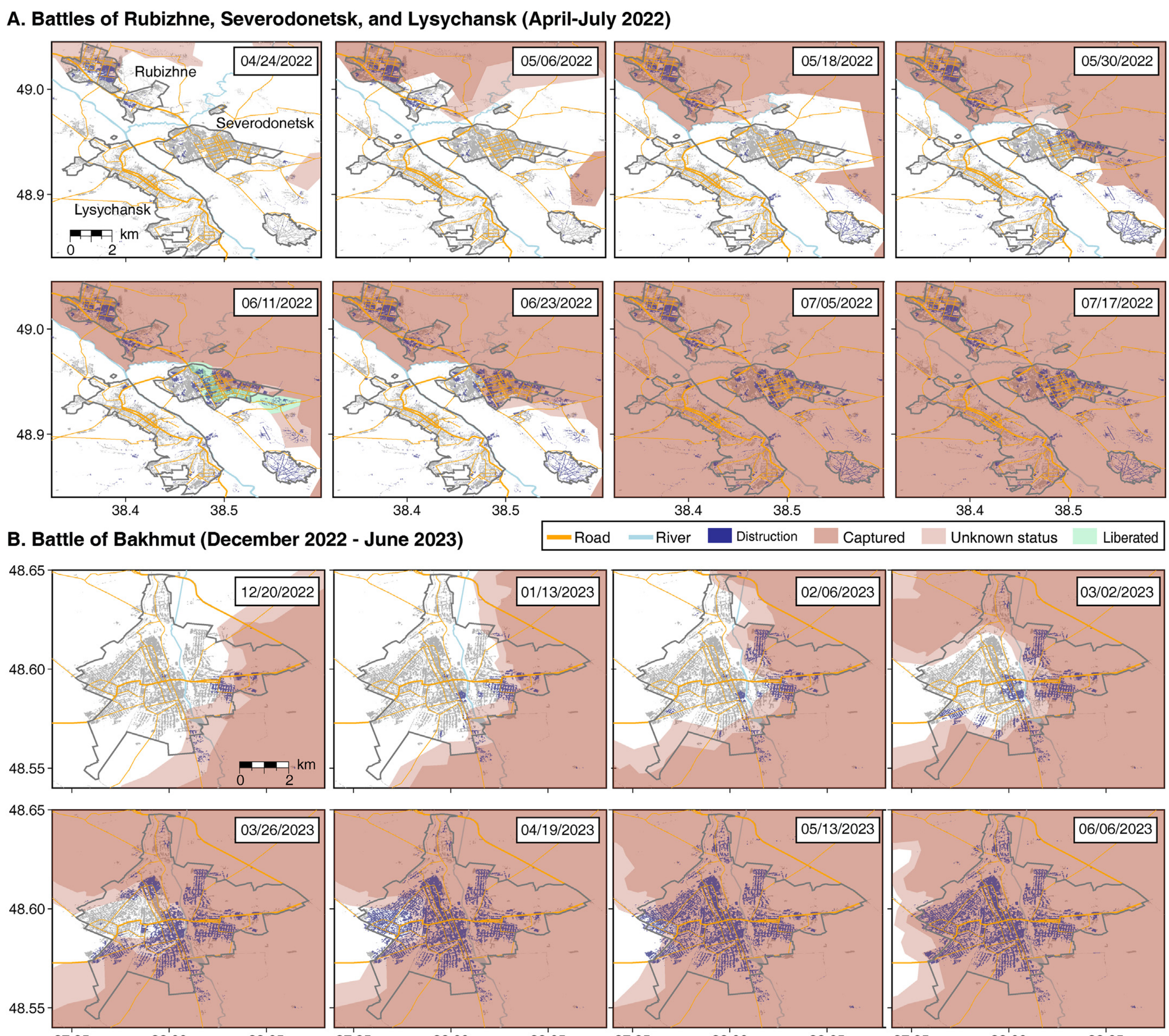

Fig. 3. Destruction of cities during the battles of Rubizhne, Severodonetsk, and Lysychansk (May–June 2022) and of Bahkmut (2022–2023) from changes in SAR coherence. Red pixels indicate lower coherence than the value derived from images acquired before the war, implying destruction or damage to buildings. a) Battles of Rubizhne, Severodonetsk, and Lysychansk. All changes are relative to a SAR acquisition on 04/12/2022. Lysychansk fell quickly after encirclement from the south. b) Battle of Bakhmut. All changes are relative to a SAR acquisition on 11/26/2022. Urban areas are shown in gray with damage in dark red. The reported progression of the Russian army, the contested areas and liberated area from OSINT (deepstatemap.live) are shown with light red, lighter red and green backgrounds, respectively. Only the pixels belong to the class "Artificial surface" was included in our damage map, which is determined by the European Space Agency (ESA) WorldCover 2021 product (https://worldcover2021.esa.int/).

a pixel. We apply a non-local filter for the coherence maps to reduce speckle noise while preserving the spatial resolution [Deledalle et al., 2015].

We first monitor the battles of Rubizhne, Sievierodonetsk, and Lysychansk from April to July 2022 (Fig. 3). The SAR coherence maps reveal the progressive destruction of Rubizhne between April 24 to May 18, 2022 (Fig. 3a). Damage to urban infrastructure becomes significant in Sievierodonetsk in the May 30, 2022 SAR acquisition, accruing until the June 23, 2022 SAR acquisition. More sporadic destruction of Lysychansk ensues across the Donets River, with the collapse of a local university and official buildings downtown. These observations are in general agreement with OSINT. The battle of Rubizhne began on March 15, 2022, and ended on May 12, 2022. The battle of Sievierodonetsk began on May 6 and ended on June 24, 2022, when Ukrainian units were ordered to retreat from the city. The battle of Lysychansk began on June 25, 2022, and ended with a Russian victory on July 2, 2022. The comparatively lower destruction of Lysychansk is explained by the rapid encirclement of the city from the south, instead of continued frontal assaults. However, OSINT data lags the SAR observations slightly. According to OSINT, the progression of the Russian army appears stable from May 2022 to June 2022, with only parts of Severodonetsk city being occupied by the Russian army. In contrast, SAR data document continuous destruction of Lysychansk during this period, indicating that the battle had already extended to Lysychansk in June. Therefore, remote sensing observations can provide complementary information related to the battlefield.

The battle of Bakhmut is the longest and bloodiest of the war so far. Although perceived of limited strategic value, Bakhmut became a military hotspot where the Ukrainian army resisted countless waves of attacks from veteran soldiers from the Wagner group reinforced with former convicts from Russian prisons. The astounding number of casualties on both sides conjured up the specter of the battle of Stalingrad (now Volgograd) in World War II. Eventually, the battle left the 400-year-old Bakhmut city in ruins, as Russia claimed victory on May 21, 2023. We monitor the Russian progression in Bakhmut from December 2022 to June 2023 using coherence maps derived from SAR interferometry (Fig. 3b). On December 20, 2022, destruction is only localized in residential areas east and south of the city that received constant assaults during that time. The January 13, 2023 acquisition reveals the destruction of a large shopping mall in Central Bakhmut, west of the Bakhmutovka River that serves as a natural defense. On February 6, 2023, SAR data show the destruction of a large residential area northeast of the city. In early March, damage intensifies in the same regions, but also spreads to the south of the city due to further attacks coming from that direction. Starting in April 2023, destruction becomes widespread in the city due to constant shelling by the Russian army, including with incendiary ammunition, but also by the detonation of explosives by Ukrainians to deny Russia the capture of standing buildings. The destruction is so absolute that the damage map reveals the individual streets that used to separate buildings and entire neighborhoods. Streets are virtually the only parts of the city with preserved coherence.

The coherence maps reveal what became a perverted tactic of this high-intensity war. The progression of troops is associated with the simultaneous destruction of the city and the final conquest is merely that of ruins. Unfortunately, a similar strategy has to be used at a smaller scale in the Ukrainian counter-attack to liberate the occupied territory, for example with the complete destruction of the Robotyne village by artillery in the Zaporizhia Oblast in August 2023.

2.3. Visible spectrum

We now focus on large-scale changes in the natural environment brought about by the war. On June 6, 2023, the Kakhovka hydroelectric dam was breached, liberating a total water volume of 18 km^3 toward the Black Sea, causing extensive flooding along the lower Dnipro River in Kherson Oblast. The ensuing flood was the largest natural disaster in Ukraine since the explosion of the Chernobyl nuclear reactor, north of Kiyv, in 1986. We use optical satellite images to describe damage to the Kakhovka dam itself and to monitor changes upstream and downstream of the Dnipro River (Fig. 4). Optical satellites acquire high-resolution images of entire landscapes of the Earth's surface in the visible range, using wavelengths between 0.4 and 0.6 m, akin to taking photographs of the ground from space. We use open-source optical images acquired from Sentinel-2 and Landsat-8 satellites, provided by ESA and NASA, respectively. The Sentinel-2 multispectral instrument provides 10 m resolution in the blue, green, and red bands along a swath of 290 km. Landsat-8 offers a 30 m resolution for similar bands, forming true-color images over a swath of 185 km. Combining images from these sensors allows us to increase the spatiotemporal resolution of observations.

The breach of the Kakhovka dam occurred toward the left bank of the Dnipro River, on the side controlled by the Russian military (Fig. 4b). Russian forces seized the hydroelectric power plant early into the invasion of Ukraine and had a small section of the connected road blown up on the right bank after their forced evacuation of Kherson Oblast in November 2022. The collapse of the dam flooded Oleshky, Kardashinka, Gola Prystan, and other villages over a width of 10 km around the previous flood plain of the Dnipro River (Fig. 4c).

The dam collapse started draining the Kakhovka artificial reservoir that was used mainly to supply hydroelectric stations, irrigation systems, and the Zaporizhzhia nuclear power plant. The reservoir, which was up to 23 km wide and 26 m deep, rapidly flushed its water, leaving the flood plain to slowly desiccate. Astonishingly, the independent reservoir of the Zaporizhzhia nuclear power plant kept its original level, sustaining the cooling of the nuclear reactors (Fig. 4d). However, the fate of the Zaporizhzhia nuclear power plant is still uncertain, as Russian forces occupy the premises, threatening the harrowing scenario of another nuclear disaster in Ukraine [Burke, 2022].

3. Discussion and conclusions

The availability of multiple remote sensing platforms operating active and passive sensors in different wavelengths provides complementary information relevant to monitoring armed conflicts. Currently, Sentinel-2 is the highest resolution open-source optical spaceborne satellite, offering a spatial ground resolution of 10 m, which is insufficient to monitor the destruction of individual buildings (Fig. S9), yet well suited to monitor floods and other large-scale surface changes. In contrast, SAR data achieves change detection through phase coherence, averaging through large pixels, virtually unaffected by cloud coverage. Detecting change of waterbodies can be conducted using SAR amplitude and optical images, but the long repeat periods of satellite observations obscure short-term hydrodynamics, such as tsunami waves along the Dnepro River emanating from the collapse of the Kakhovka Hydroelectric Station (Fig. 4).

Although the nightlight and optical data are processed following standard procedures (Supplementary Material A and C), special processing of SAR imagery is required to maintain high-resolution in urban environments [e.g., Yun et al., 2015]. Specifically, we consider the influence of coherence loss from snow melt and changes in vegetation, and further mitigate the impact of speckle noise while preserving the resolution with a non-local filter [Deledalle et al., 2015]. The proposed procedures allow for tracking time series of change in the battlefield (Supplementary Material B). We also cross-validate the assessment of destruction using ascending and descending SAR data (Figs. S4–5), and by comparing the results with OSINT when available (Fig. 3).

Spaceborne remote sensing offers a versatile tool to safely monitor the impact of armed conflicts over multiple spatiotemporal scales. Open-access data acquired in the near-infrared, visible, and microwave bands provide proxies for socio-economic changes at the country scale, alterations in the environments at the regional scale, and the destruction of buildings, neighborhoods, and entire cities. As high-intensity wars in urban environments proliferate, for example with the ongoing Israelo-Palestinian war in the Gaza Strip, spaceborne remote sensing emerges

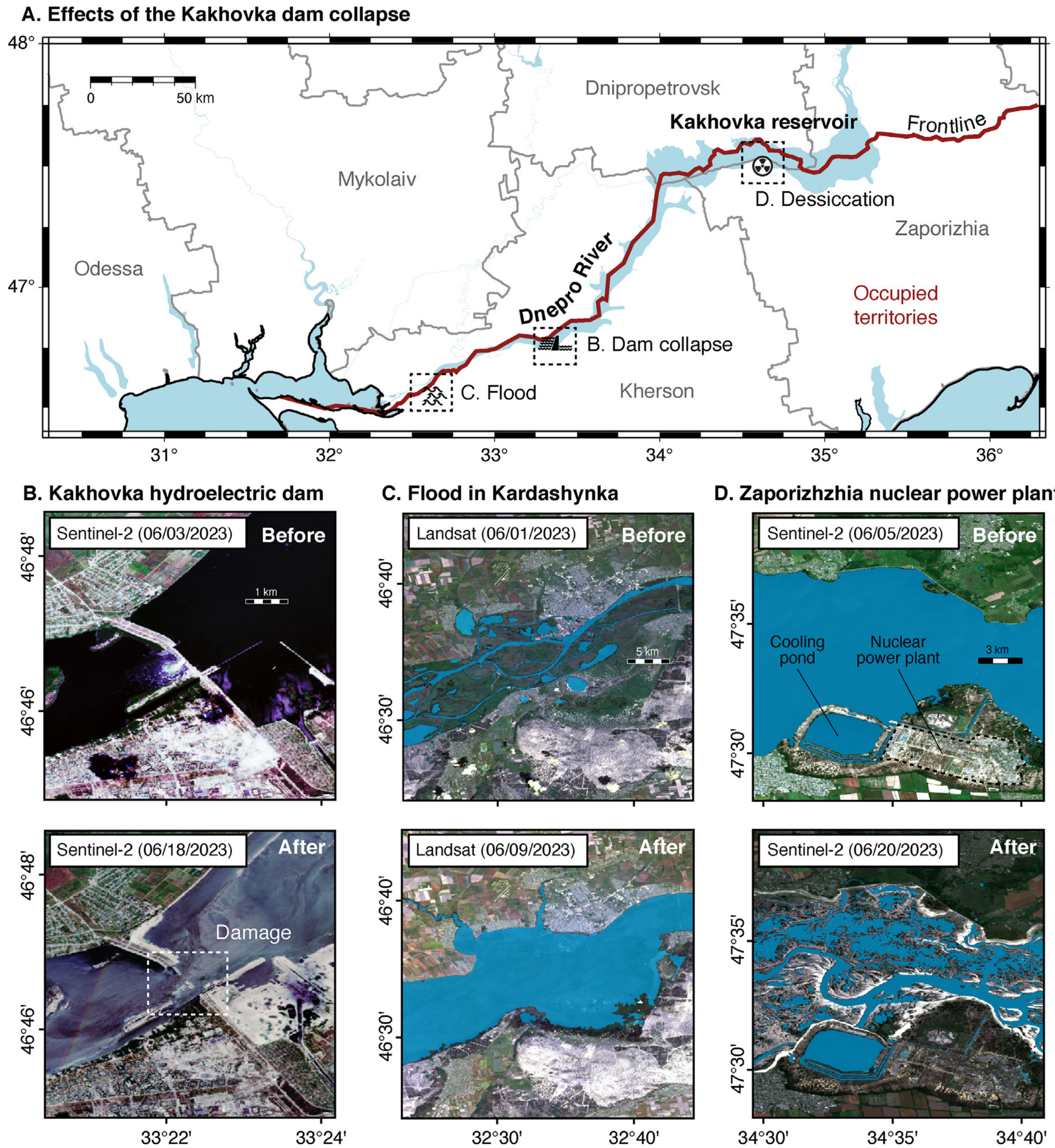

Fig. 4. Remote sensing of the breach of the Kakhovka dam and its effects on the environment. a) Location of the Kakhovka reservoir, the Kakhovka hydroelectric power station, and the Zaporizhzhia nuclear power plant along the Dnepro River in Kherson oblast. b) Images of the Kakhovka dam taken before and after the breach on June 6, 2023, showing the obliteration of the Russian-controlled side of the dam. c) Extent of the resulting flood along the lower Dnipro River. d) Before and after images of the Kakhovka reservoir showing drainage of the basin and the providential persistence of the cooling pond next to the Zaporizhzhia nuclear power plant.

as a crucial source of information [Cardille et al., 2023; Josh et al., 2023]. Spaceborne sensors complement other forms of OSINT by offering uninfringed access to high-resolution, unbiased information, enhancing our ability to grasp the true impact of war on the ground: The real story of war is destruction.

Data availability statement

The nighttime lights data are obtained via the Black Marble dataset of NASA (https://blackmarble.gsfc.nasa.gov/VNP46A2.html). The Sentinel-1 SAR images are available through ESA's Copernicus Copernicus Open Access Hub. Landsat 8 and 9 images can be found via the Earth Explorer interface provided by the USGS (https://earthexplorer.usgs.gov/). The Sentinel-2 optical images can be accessed via ESA's Copernicus Copernicus Open Access Hub. We curate the OSINT data for the frontline, defense line, and location of military targets available on https://deepstatemap.live/. All the data used in Figs. 2–4 are available on zenodo.org (https://zenodo.org/records/10479609).

CRediT authorship contribution statement

Hang Xu: Writing – review & editing, Writing – original draft, Methodology, Data curation. **Sylvain Barbot:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Teng Wang:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nhres.2024.01.006.

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