Chapter 4

MONITORING ECONOMIC ACTIVITIES: LEVERAGING SATELLITE AND REMOTE-SENSING TECHNOLOGIES

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Understanding disruptions to economic activities in conflict-affected regions such as Sudan is essential for policymakers, humanitarian organizations, and researchers seeking to develop effective response strategies. However, traditional data collection methods, such as official government statistics and household surveys, become unreliable or impractical in these contexts due to security risks, displacement, and institutional breakdowns. In such environments, satellite and remote-sensing technologies provide a powerful alternative, offering near real-time, scalable, and objective insights into economic disturbances, infrastructure damage, population displacement, and environmental degradation. Advances in Earth observation technologies now allow researchers to monitor the economic consequences of conflicts with great accuracy and efficiency, even in regions where on-the-ground data collection is impossible (Hoogeveen et al. 2016; Hoogeveen and Pape 2020; Abay et al. 2023).

Among the most widely used remote-sensing data, nightlight has emerged as a key proxy for economic activity. Satellites such as the Visible Infrared Imaging Radiometer Suite (VIIRS) and the Defense Meteorological Satellite Program capture nightlight imagery, allowing researchers to track changes in economic intensity across urban and industrial regions (Ezran et al. 2023). Typically, brighter nightlight corresponds to increased commercial activity, urbanization, and industrial development. These data have proven particularly valuable in conflict settings, where sudden drops in nightlight intensity can indicate economic downturns, displacement of populations, or destruction of infrastructure. However, nightlight data also have limitations—they are affected by cloud cover, do not capture daytime economic activities, and cannot provide insights into industries that do not rely on artificial lighting.

Recently, nitrogen dioxide (NO_2) emissions estimated from satellite data have gained increasing favor as an economic proxy (Morris and Zhang 2019). NO_2 is closely linked to industrial activity, transportation networks, and power generation, making it a useful indicator of production and energy consumption (Goldberg et al. 2021). Satellite instruments such as Sentinel-5P/TROPOMI and OMI/Aura provide high-resolution NO_2 concentration data, allowing researchers to assess economic disruptions with near real-time precision. Unlike nightlight data, NO_2 emissions capture daytime activities and have a short atmospheric lifespan, ensuring that emission levels reflect recent economic behavior. However, interpreting NO_2 data requires careful calibration, as atmospheric conditions such as wind patterns and precipitation can influence emissions dispersion.

Sudan provides a critical case for examining the use of satellite and remote-sensing technologies in monitoring economic activities under conflict conditions. The country has faced recurrent political instability and, most recently, the large-scale armed conflict that erupted in April 2023, between the Sudanese Armed Forces (SAF) and the Rapid Support Forces (RSF). The conflict has caused severe disruptions to livelihoods, infrastructure, and economic systems—particularly in Khartoum, Sudan's principal economic hub. This chapter applies remote-sensing data to analyze how these disruptions have reshaped economic activity patterns across Sudan in near real-time.

The conflict in Sudan and its economic implications

The conflict between the SAF and RSF has severely disrupted economic activities, infrastructure, and public services, with Khartoum suffering the most intense impacts. Reports indicate widespread bank closures, shortages of essential goods, and mass displacement, leading to worsening humanitarian conditions. As of mid-October 2023, more than 70 percent of Sudan's healthcare facilities had ceased operation due to violent clashes, with disruptions to Khartoum's centralized medical infrastructure leaving millions with limited access to health services (UNHCR 2023). The displacement crisis was intensifying; as of February 2026, 7 million people had been internally displaced, while 4.5 million had fled to neighboring countries, including Chad, Egypt, South Sudan, Ethiopia, and the Central African Republic (UNHCR 2026). The ongoing fighting had also strained regional resources, increasing food insecurity and putting additional pressure on host communities (Siddig et al. 2023).

The economic consequences of the Sudanese conflict extend beyond immediate humanitarian concerns. Disruptions in trade, industry, and agriculture have significantly weakened Sudan's economy. Infrastructure damage and disruptions to domestic and international trade have further diminished the country's productive capacity, making economic recovery increasingly difficult.

The economic crisis is particularly concerning due to the damage sustained by Khartoum—Sudan's primary commercial hub and home to its largest industrial, financial, and service sectors. Industrial statistics for 2011 reported about 248,000 industrial establishments in all of Sudan, 64 percent of which were based in Khartoum (Sudan, Ministry of Environment, Forestry and Urban Development and UN-Habitat 2014). Khartoum has also been a major trade center for agricultural commodities, linking rural production areas to domestic and international markets. At the onset of the conflict, the city's economic activity nearly collapsed as businesses were shuttered and residents fled (Abushama et al. 2023; Kirui et al. 2023). The decline of economic activity in Khartoum has also had serious effects on supply chains, employment, and overall market stability.

Using satellite data to monitor economic disruptions

Recent studies highlight the growing importance of NO_2 satellite data in economic analysis (Guo et al. 2024). Morris and Zhang (2019) demonstrated how NO_2 emissions could serve as an independent measure of economic growth, particularly in cases where official GDP figures may be unreliable. Their study validated data on China's industrial activity by correlating NO_2 emissions with economic output, revealing discrepancies in official statistics. Ezran and colleagues (2023) expanded on this concept by integrating NO_2 satellite data with nightlight imagery to refine the estimation of business cycles. Their research found that NO_2-based economic estimates more accurately tracked real-time business fluctuations than nightlight data alone, particularly in developed economies where NO_2 emissions closely follow industrial production. Furthermore, their study demonstrated that NO_2 data are highly responsive to economic shocks, such as the downturn experienced during the COVID-19 pandemic, highlighting its potential as a near-instantaneous economic monitoring tool.

Beyond NO_2 and nightlight data, additional satellite-based indicators further enrich economic assessments. Land cover changes, observed through Landsat and Sentinel-2 imagery, reveal patterns of urban expansion, destruction, and shifts in agricultural land use. Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), are instrumental in tracking agricultural output and food security risks in conflict-affected regions. Maritime trade activity, monitored via Automatic Identification System (AIS) data, provides insights into disruptions in supply chains and shifts in regional commerce. By integrating these multiple data sources, researchers can develop a more comprehensive, multidimensional view of economic activity in unstable environments.

Given the challenges of collecting accurate socioeconomic data in conflict zones, the capacity of remote sensing to provide large-scale observations over inaccessible areas makes it an indispensable tool for monitoring economic conditions, guiding policy interventions, and supporting humanitarian operations (Henderson et al. 2012). In the case of Sudan, remote sensing provides important information on the evolution of economic activities before and after the outbreak of conflict. By analyzing changes in NO_2 emissions and nightlight intensity, this study provides a near real-time assessment of how economic activity patterns have been reshaped by the ongoing conflict. The findings carry significant implications for food security, infrastructure planning, and crisis response strategies, particularly in regions where ground-based economic data are unavailable or unreliable. The following sections provide an in-depth discussion of the methodologies employed, findings from the Sudan case study, and broader policy implications for integrating satellite remote sensing into economic monitoring frameworks in conflict-affected regions.

Methodology

Nitrogen dioxide (NO_2) is a harmful air pollutant released from both human and natural sources, including industrial processes, power generation, transportation, wildfires, lightning, and soil microbial activity. Among anthropogenic sources, fossil fuel combustion—especially from vehicles, power plants, and industrial operations—is the primary driver of NO_2 emissions (Keola and Hayakawa 2021). Because of its strong association with human activity, NO_2 serves as a valuable proxy for economic and industrial performance, particularly in areas where conventional economic data are limited or unreliable. Analyzing the spatial and temporal patterns of NO_2 helps identify activity hotspots and shifts linked to human development. Monitoring these trends over time enables policymakers and planners to evaluate economic dynamics, assess the effectiveness of interventions, and design strategies to reduce air pollution.

The Sentinel-5P OFFL NO_2 product marks a significant advancement in Earth observation and atmospheric monitoring (ESA 2018). Developed by the European Space Agency's Sentinel-5 Precursor mission, it leverages the TROPOspheric Monitoring Instrument (TROPOMI)—a state-of-the-art imaging spectrometer—to deliver high-resolution measurements of atmospheric gases, including NO_2 (Goldberg et al. 2021).

The Sentinel-5P NO_2 product delivers a comprehensive range of insights, including:

- High-resolution maps of NO_2 concentrations at approximately 1 km^2 spatial resolution
- Near real-time measurements, enabling timely assessments of air pollution and economic activity
- Vertical profiles and time-series data, allowing researchers to analyze long-term and short-term NO_2 trends

These capabilities make Sentinel-5P a powerful tool for tracking NO_2 emissions and their association with human activity. It has also been instrumental in detecting conflict-related disruptions in economic activity (Cooper et al. 2022). In areas affected by armed conflict or political instability, disruptions to industrial operations, restricted transportation, and shutdowns of economic hubs often lead to significant declines in NO_2 emissions—serving as a clear signal of reduced human and industrial activity.

In the Sudan case study, NO_2 satellite data were used to examine both the baseline distribution of economic activities and the impact of conflict on emissions patterns over time. To understand the preconflict economic landscape, we first construct an NO_2 concentration baseline map for 2022, identifying the locations of human settlements, industrial hubs, and major economic activity areas. This is achieved by processing daily NO_2 data from 2022, covering Sudan at a high temporal and spatial resolution. The dataset is then aggregated to compute the annual average NO_2 concentration at the pixel level, allowing us to create a spatially explicit map of economic intensity across Sudan. By comparing NO_2 levels with known urban centers and industrial zones, we can assess whether NO_2 concentrations align with established economic hubs such as Khartoum, Nyala, and El-Obeid. It also serves as a foundational dataset for tracking subsequent changes in emissions patterns related to conflicts. The baseline NO_2 map captures Sudan's pre-war industrial footprint, highlighting major cities and manufacturing zones, which were expected to experience significant disruptions during wartime.

To assess the impact of conflict on economic activity at the onset of the war, we examined NO_2 concentration trends in key cities before and after the outbreak of hostilities. Our approach combines high-resolution spatial visualization at the pixel level with quantitative aggregation at the administrative unit level, ensuring a comprehensive evaluation of conflict-induced economic disruptions. The analysis has two components: (1) mapping NO_2

concentrations at the pixel level to capture localized changes before and after the conflict, and (2) analyzing temporal NO_2 emission trends over April 2023, distinguishing between cities directly affected by conflict and those experiencing indirect economic disruptions.

To visualize the spatial distribution of emissions, we generated high-resolution NO_2 concentration maps at the 1×1 km^2 pixel level for two time periods: April 1–7, 2023 (before the conflict), and April 14–21, 2023 (during the conflict). These two maps provide a detailed representation of NO_2 fluctuations across different regions, enabling us to identify specific cities and industrial hubs that experienced the most significant economic slowdowns due to the conflict. This pixel-level analysis highlights localized variations in economic activity, distinguishing between areas with severe economic contractions and those that remained relatively stable. For instance, Khartoum, Bahri, and Omdurman, which were major battlegrounds, experienced disruptions in industrial output, transportation networks, and commercial activities. Conversely, Kassala, which reportedly was largely insulated from direct fighting, showed limited impact from the conflict.

While pixel-level mapping provides detailed insights, a systematic quantification of these changes at the municipal level—referred to as the administrative unit—is necessary to facilitate regional comparisons. To accomplish this, we calculated the average NO_2 concentration for each five-day interval throughout April 2023 at the administrative unit level. A series of representative cities were selected and grouped into two categories: conflict-affected and less- or non-conflict-affected. The selection of cities was informed by multiple sources, including recommendations from local experts, information from news and media reports, and insights obtained through virtual meetings with local staff. These selections were subsequently verified using conflict event data from Armed Conflict Location and Event Data (ACLED) (Ali and Ada 2023; Ali 2023). By aggregating NO_2 emissions data, we assessed how different administrative units responded to the conflict, identifying areas that experienced sharp economic declines and those that remained relatively stable, including both units directly affected by conflict and units outside the conflict zone. This approach provides a clearer understanding of how the conflict reshaped economic dynamics over time.

While NO_2 data provide near real-time insights into economic activities, we also incorporated VIIRS nightlight data to validate our findings (NCEI 2023). Nightlight intensity serves as a complementary economic indicator, capturing nighttime activity patterns in urban and industrial areas. However, VIIRS nightlight data is only available at monthly intervals and has a 3–4-month processing delay, making it more suitable for long-term trend validation rather than immediate real-time monitoring.

Thus, for the nightlight analysis, we utilized nightlight data from March 2023 as a preconflict baseline and May 2023 as the postconflict observation. As with the NO_2 data, we analyzed changes in nightlight intensity across key cities to assess whether trends observed in nightlight data aligned with NO_2-based findings. By comparing these datasets, we ensured the reliability and robustness of our assessment, reinforcing the conclusion that Sudan's conflict zones experienced substantial economic disruptions following the conflict's outbreak.

Results and discussion

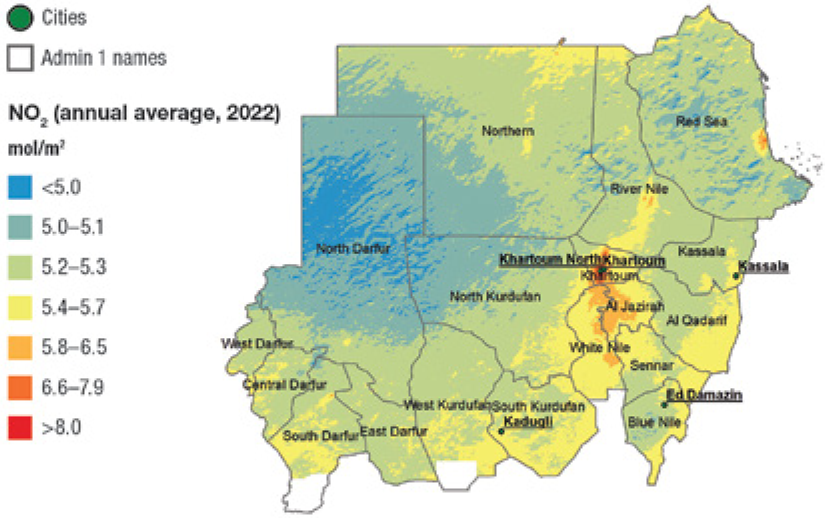
The annual mean TROPOMI-derived pixel-level NO_2 concentrations for 2022 (expressed in moles per square meter, mol/m^2, representing the total vertical column density of atmospheric NO_2) serve as a foundational baseline to demonstrate the utility of NO_2 as a proxy for mapping and monitoring economic activity across Sudan (Figure 4.1). By establishing this baseline, we could identify industrial hotspots and assess how spatial patterns of NO_2 emissions correspond to ground-level economic activities, thus providing a reference for future comparisons and monitoring.

The NO_2 distribution map for 2022 reveals distinct spatial heterogeneity across Sudan, highlighting variations in emissions intensity related to urbanization, industrial activity, and transportation infrastructure:

- High NO_2 concentrations are predominantly observed in urban and industrial regions, where emissions from factories, power plants, and heavy vehicular traffic are most significant.
- The cities of Khartoum and Omdurman, and other urban areas, exhibit the highest NO_2 levels, reflecting their roles as major economic hubs with dense industrial operations, extensive road networks, and significant energy consumption.
- Rural areas, particularly in western and southern Sudan, show significantly lower NO_2 levels, a result of limited industrial activity, sparse transportation infrastructure, and lower population density.

By establishing this annual baseline, we could systematically compare preconflict NO_2 emissions with postconflict patterns, allowing for a detailed assessment of the impact of the April 2023 conflict on economic activity

FIGURE 4.1 Average of NO_2 concentration (mol/m^2) in 2022



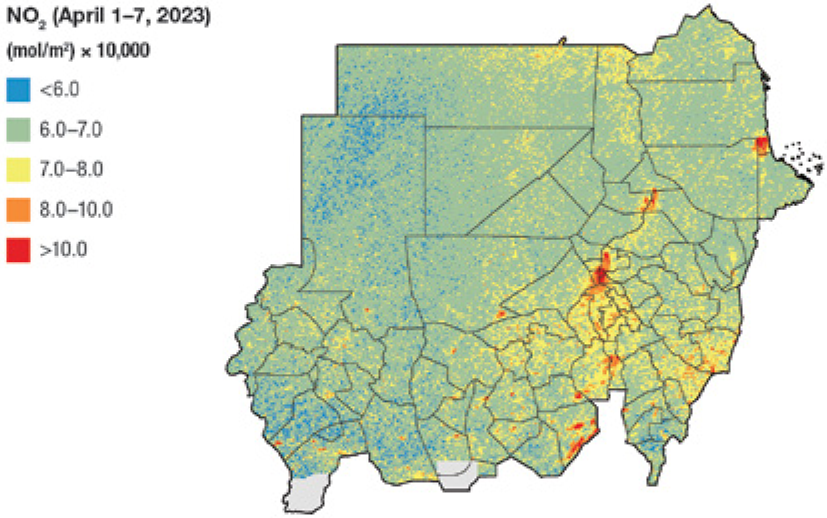
Source: Authors' depiction based on Sentinel-5P OFFL TROPOMI-derived NO_2.
Note: The figure uses the alternative spellings of Al Qadarif for El-Gedaref and Al Jazirah for Aj Jazirah.

across different regions of Sudan. The highest intensity of armed confrontation was recorded in Khartoum State, particularly in Khartoum City, where the military headquarters and key public institutions are concentrated. The conflict also affected the twin cities of Omdurman and Khartoum North, though fighting in these areas was somewhat less intense. Given that Khartoum serves as Sudan's primary economic and administrative hub, these hostilities had profound implications for commercial activity, infrastructure stability, and population displacement.

Figures 4.2 and 4.3 illustrate the spatial distribution of NO_2 levels before and during the conflict based on Sentinel-5P OFFL TROPOMI-derived NO_2 data.

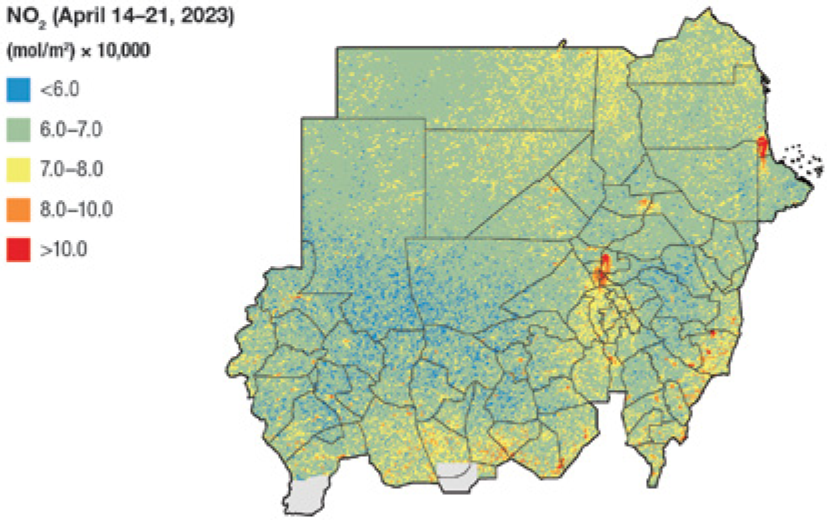
- Preconflict period (April 1–7, 2023): NO_2 concentrations were relatively high and widespread, particularly in Khartoum and major industrial and transportation corridors across central, eastern, and southern Sudan. This reflects normal economic activity, including industrial emissions and vehicular movement.

FIGURE 4.2 NO_2 levels (mol/m^2) in Sudan before the conflict (April 1–7, 2023)



Source: Authors' depiction based on Sentinel-5P OFFL TROPOMI-derived NO_2.

FIGURE 4.3 NO_2 levels (mol/m^2) in Sudan during the conflict (April 14–21, 2023)



Source: Authors' depiction based on Sentinel-5P OFFL TROPOMI-derived NO_2.

- During conflict (April 14–21, 2023): Following the eruption of conflict, there was a notable decline in NO_2 levels across conflict-affected regions, particularly in Khartoum, River Nile state (Atbara area), Gedaref state, Aj Jazirah state, and other parts of Central Sudan. This reduction suggests a sharp decrease in economic and industrial activity, likely due to business closures, reduced transportation, and displacement of the workforce.

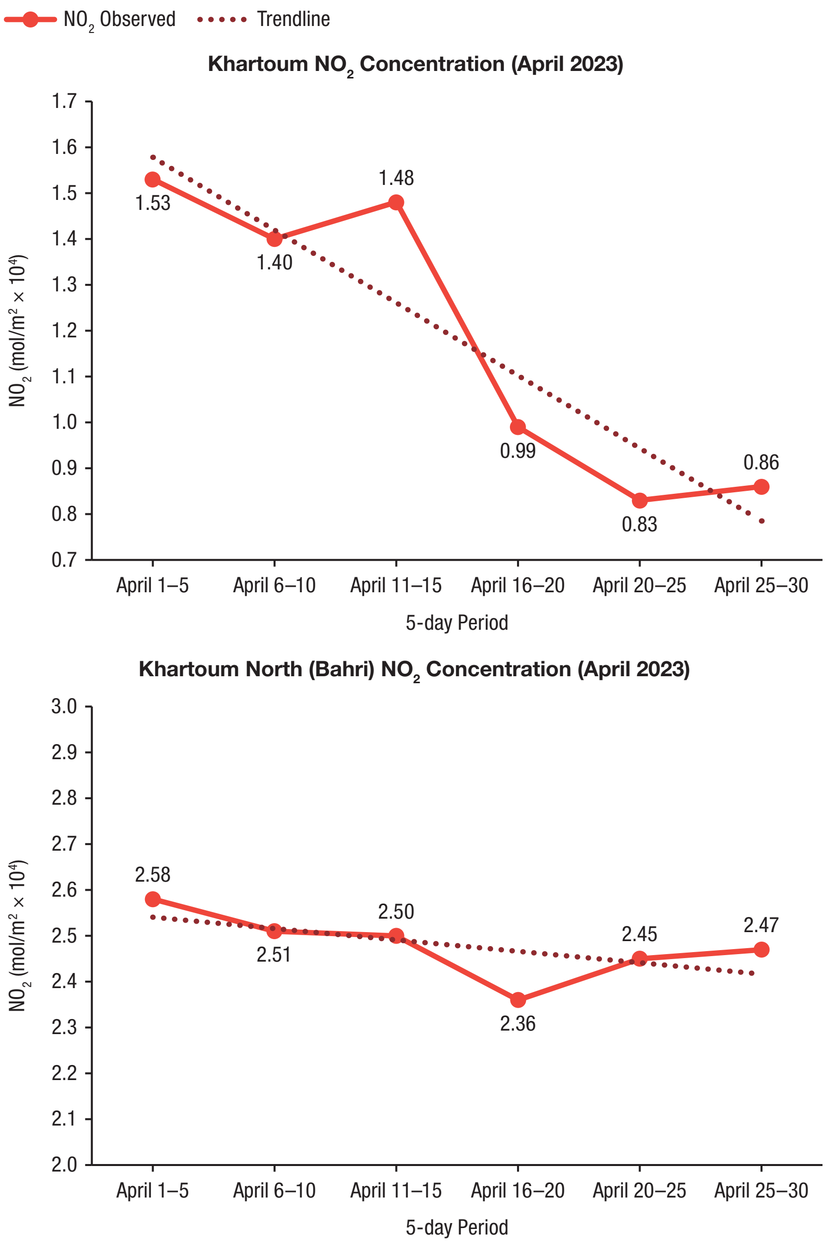
These findings highlight the immediate economic consequences of the conflict, as industrial and vehicular emissions—key proxies for economic activity—declined significantly in heavily affected regions. The spatial heterogeneity of NO_2 changes also underscores the varying degree of conflict-related disruptions, with some regions experiencing steeper declines due to the greater severity of hostilities and population displacement.

Beyond the comparison of NO_2 concentration snapshots before and after the conflict, we also examined trends throughout the entire month of April, utilizing daily NO_2 observations from satellite data. Figures 4.4 and 4.5 provide a closer look at the mean NO_2 concentrations at the administrative level for April 2023, distinguishing between regions directly impacted by the conflict and those that remained relatively unaffected. The data indicate notable shifts in NO_2 levels around Greater Khartoum, where a clear downward trend is observed in Khartoum and Khartoum North following the outbreak of conflict on April 15. The abrupt cessation of movement in and around Khartoum, resulting from mass displacement and the disruption of industrial and commercial activities, likely contributed to the reduction in NO_2 emissions, reflecting the broader economic slowdown triggered by the conflict.

In contrast to the sharp decline in NO_2 concentrations observed in Khartoum state, several regions that were less directly affected by the conflict, such as Ed Damazin, Kadugli, and Kassala, show an upward trend in NO_2 levels throughout April, as shown in Figure 4.5. These areas, located farther from the immediate conflict zones, experienced increased human activity and movement, as they became major destinations for internally displaced persons (IDPs) fleeing the violence in Khartoum. The influx of IDPs, coupled with the continued operation of transportation networks, commercial activity, and temporary settlements, contributed to the rise in NO_2 emissions between April 16 and 30.

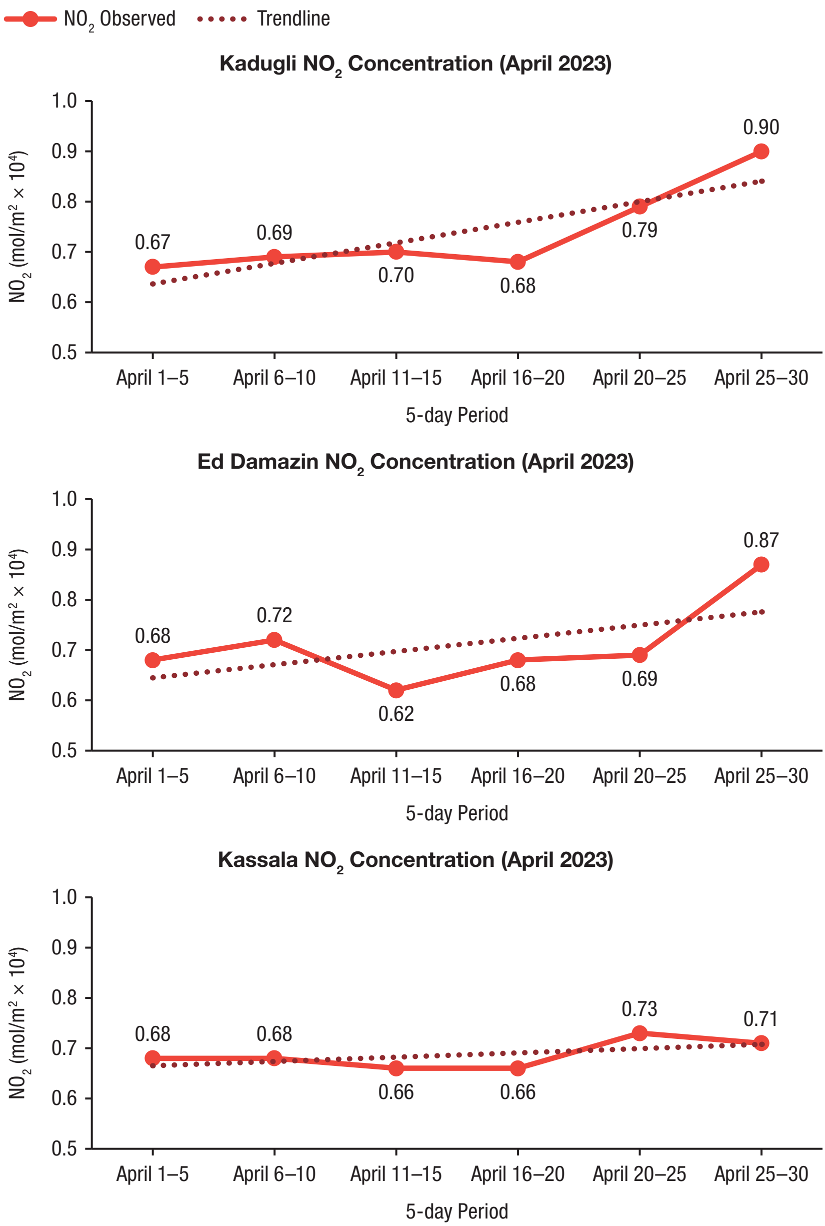
Over time, Kassala evolved into a de facto administrative and economic hub, with several government offices and businesses relocating there to continue operations. However, many migrants only passed through Kassala and

FIGURE 4.4 NO_2 levels (mol/m^2) in the Khartoum cities (conflict-affected area)



Source: Authors' calculation based on Sentinel-5P OFFL TROPOMI-derived NO_2.

FIGURE 4.5 NO_2 levels (mol/m^2) in Ed Damazin, Kadugli, and Kassala (less conflict-affected areas)



Source: Authors' calculation based on Sentinel-5P OFFL TROPOMI-derived NO_2.

other cities on their way to more permanent settlements, including in Saudia Arabia, Egypt, and other neighboring countries.

As a complement to the analysis of NO_2 concentrations, we also analyze VIIRS nightlight data. Our analysis focused on two key cities: Khartoum, which experienced direct conflict, and Ed Damazin, which saw fewer conflict-related disturbances. To account for potential seasonal variations, we also examined VIIRS nightlight data from March and May 2022, ensuring that any observed changes in 2023 were primarily attributable to the conflict rather than seasonal effects or temporary changes in infrastructure.

Figure 4.6 presents a comparative analysis of nightlight intensity before and after the onset of the conflict. The data clearly show a marked decrease in nightlight intensity from March 2023 to May 2023, aligning with the observed decline in NO_2 concentrations. This reduction suggests a significant disruption in economic activity, infrastructure usage, and urban illumination due to the conflict. In contrast, an analysis of nightlight intensity for the same period in 2022 (March to May) reveals no substantial differences, indicating that, in the absence of conflict, seasonal or external factors had a minimal impact on nightlight variability.

To facilitate a comparative analysis, we also examined changes in nightlight intensity in Ed Damazin, a region where NO_2 levels remained stable (Figure 4.7). Consistent with the NO_2 observations, no significant decrease in nightlight intensity was detected, suggesting that economic activity in this area was relatively unaffected by the conflict. Interestingly, some locations within Ed Damazin exhibited increases in nightlight intensity, potentially reflecting an influx of IDPs or shifts in local economic activities. These spatiotemporal patterns observed in nightlight data closely align with those seen in NO_2 measurements.

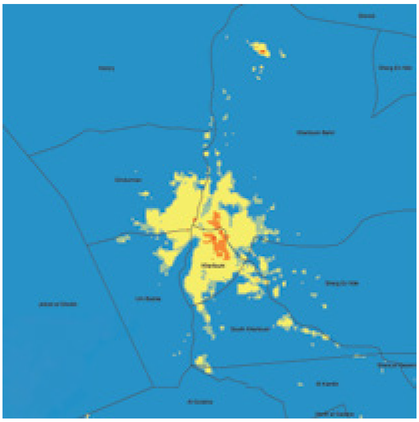
TROPOMI-derived weekly mean ground-level NO_2 concentrations for the periods of April 1–7, 2023 (pre-war) and April 14–21, 2023 (first week of the conflict) across selected cities that were either directly affected by conflict or remained relatively stable are shown in Table 4.1. These results indicate that all conflict-affected urban regions experienced a decline in NO_2 concentrations, with the exception of El-Geili in northern Khartoum state and Sawakin in Red Sea state, both of which exhibited a slight increase. The rise in NO_2 levels in El-Geili is likely attributable to the presence of a major oil refinery, which remained operational due to its strategic economic importance, and to the influx of IDPs from central Khartoum and Khartoum North. Similarly, Sawakin did not experience a decline, as it is geographically distant from the conflict's epicenter and remained largely unaffected during the initial phase of the war.

FIGURE 4.6 Nightlight intensity (nanowatts per square centimeter per steradian, nW·cm^{-2}·sr^{-1}) of March 2022 (upper left), May 2022 (upper right), March 2023 (bottom left), and May 2023 (bottom right)

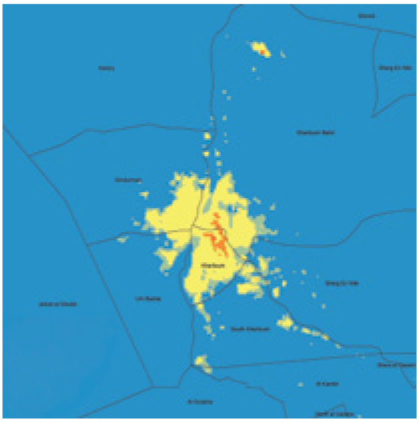
Night light
nanoWatts/sr/cm²

<5.0 | 5.0–10.0 | 10.1–50.0 | 50.0–100.0 | >100

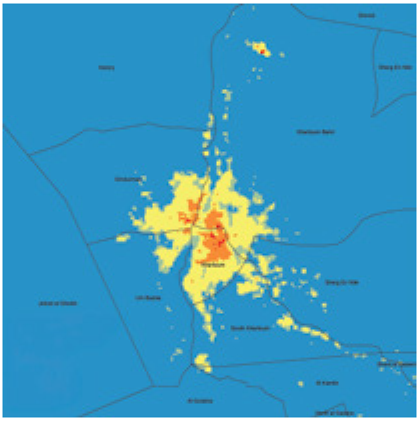
A. March 2022



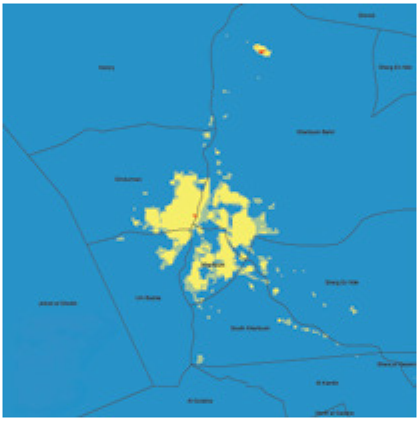
B. May 2022



C. March 2023



D. May 2023

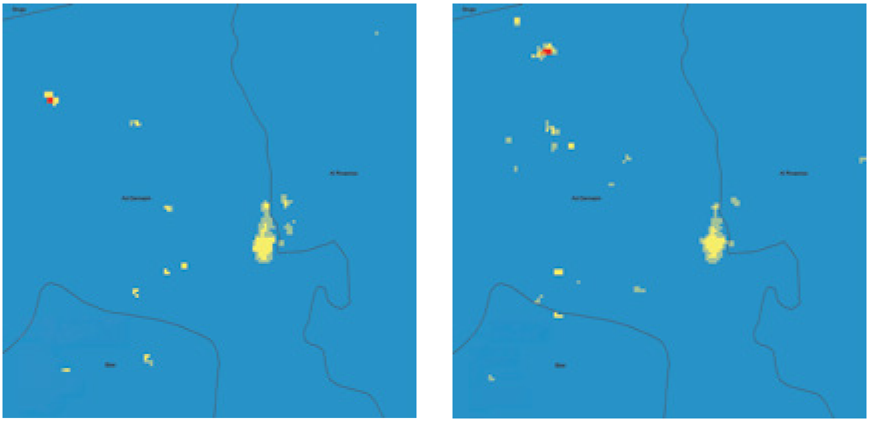


Source: Authors’ calculation based on VIIRS nightlight data.

FIGURE 4.7 Nightlight intensity (nanowatts per square centimeter per steradian, nW·cm^{-2}·sr^{-1}) of March 2023 (left) and May 2023 (right).

Night light
nanoWatts/sr/cm² <5.0 5.0–10.0 10.1–50.0 50.0–100.0 >100

A. March 2023 B. May 2023



Source: Authors' calculation based on VIIRS nightlight data.

TABLE 4.1 NO_2 concentrations (mol/m^2) and changes in selected cities of Sudan in April 2023

City	April 1–7,2023 (mol/m^2) *10000	April 14–21,2023 (mol/m^2) *10000	Change (percent)	Conflict?
Khartoum	1.53	1.01	–33.99	Yes
El-Geili	0.79	0.81	2.53	Yes
Es Sileit	0.76	0.73	–3.95	Yes
Khartoum North	1.03	0.85	–17.48	Yes
Omdurman	2.58	2.39	0.00	Yes
Sawakin	0.97	0.99	2.06	No
Kassala	0.68	0.68	0.00	No
El-Fashir	0.67	0.64	–5.88	No
Kadugli	0.69	0.69	0.00	No
Ed Damazin	0.68	0.68	0.00	No

Source: Authors' calculation based on Sentinel-5P OFFL TROPOMI-derived NO_2 data.

Among the cities that recorded the most significant NO_2 reductions, Khartoum saw the steepest decline (−34%), followed by Khartoum North (−17%), El-Fashir (−6%), and Es Sileit (−4%). The substantial decreases in Khartoum and Khartoum North align with their status as key economic and administrative hubs, where intense fighting led to the closure of industries, commercial activities, and transportation networks. El-Fashir and Es Sileit—both of which host RSF military bases targeted by the SAF—also exhibited notable NO_2 reductions, likely reflecting disruptions in industrial operations and vehicular movement.

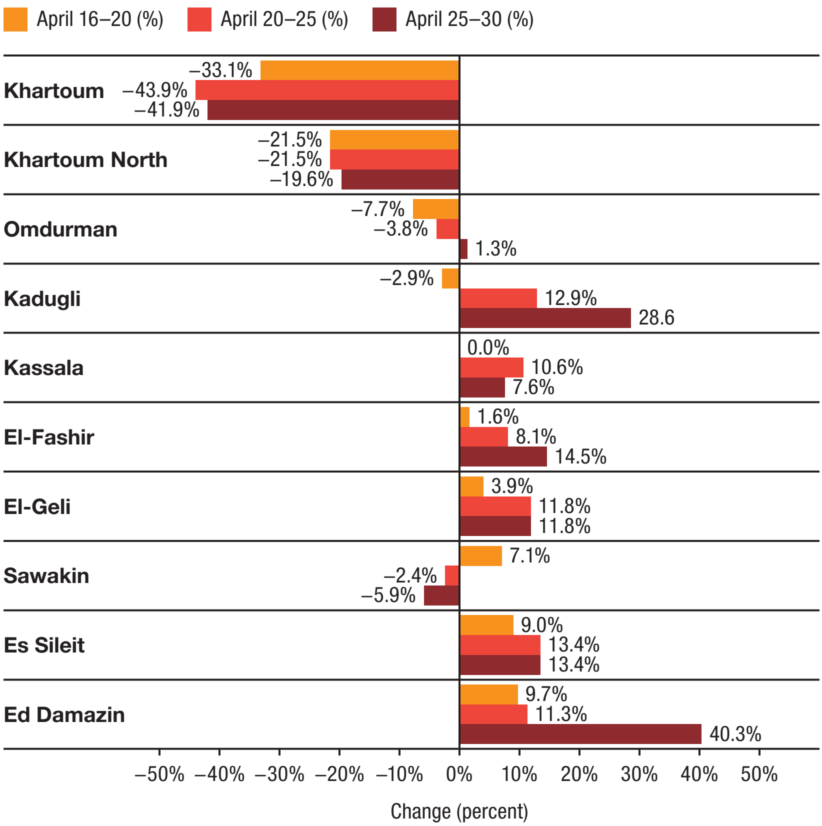
In contrast, cities outside the primary conflict zones showed either no significant change or a slight increase in NO_2 levels. The minor uptick in NO_2 concentrations observed in some nonconflict areas is likely due to their role as receiving centers for IDPs. As people fled war-affected regions, certain cities—such as Kassala, Ed Damazin, and Kadugli—may have experienced a temporary increase in transportation activity and localized emissions, contributing to stabilized or slightly elevated NO_2 levels.

We also analyzed percentage changes in NO_2 concentrations over three distinct periods (April 16–20, April 20–25, and April 25–30, 2023) relative to the immediate pre-war baseline (April 10–15, 2023) (Figure 4.8). These time windows allow a detailed breakdown of how emissions fluctuated in both conflict-affected and relatively stable regions, offering insights into the dynamics of economic disruptions, industrial slowdowns, and population displacement.

In Khartoum, NO_2 concentrations dropped between 33 and 44 percent, while in Khartoum North, they declined between 20 and 22 percent during the three periods analyzed.[1] These two cities were at the heart of the conflict and experienced heavy fighting, large-scale displacement, and a near-total economic standstill. The drastic reduction in NO_2 emissions in these areas was primarily linked to mass civilian evacuations, which significantly reduced vehicle traffic and transportation-related emissions. Additionally, industrial shutdowns, particularly in Khartoum North, where there are a significant number of factories and manufacturing plants, contributed to the observed declines. The closure of key industrial facilities and disruptions in power generation further contributed to the decrease in NO_2 emissions, reflecting a steep contraction in economic activity. The economic paralysis in Khartoum

1 Khartoum, Khartoum North, and Omdurman are the three cities that make up the Greater Khartoum metropolitan area. Khartoum serves as the national capital and administrative center; Khartoum North is a major industrial and commercial zone; and Omdurman, the largest of the three by population, is a cultural and historical hub. The cities are interconnected by a network of bridges and roads, forming Sudan's primary urban and economic core.

FIGURE 4.8 Changes in NO_2 concentrations (mol/m^2) in selected cities for three periods after the conflict began compared to the April 11–15 period



Source: Authors' calculation based on Sentinel-5P OFFL TROPOMI-derived NO_2 data.

was further reinforced by the halt in business operations, the shutdown of government institutions, and the widespread collapse of local markets.

The case of Sawakin, a port city in northeastern Sudan, is particularly notable, as it initially exhibited minimal change in NO_2 levels in the first few days of the conflict. This suggests that the city continued to operate during the initial phase of the war, benefiting from its distance from the primary conflict zone. However, in subsequent days, a sharp decline in NO_2 levels was observed, likely due to the reduction in import and export activity, disruptions in logistical supply chains, and particularly the loss of connectivity between Khartoum and major trade hubs, as conflict-related instability made it difficult to maintain normal trade flows. Likewise, the decline in vehicles using transportation and trade routes to and from Port Sudan likely contributed to this decline, as well.

While conflict-affected cities witnessed significant declines in NO_2, several other regions exhibited a gradual increase in emissions. Cities such as El-Geili, Kassala, El-Fashir, Ed Damazin, and Kadugli saw a steady rise in NO_2 levels in April 2023. These trends can be attributed to the influx of IDPs and shifts in local economic activity. Many of these regions served as primary destinations for IDPs fleeing from conflict zones. Kassala and El-Geili, for example, saw increased emissions due to heightened transportation activity and the arrival of large numbers of refugees. Ed Damazin and Kadugli functioned as transitional hubs where displaced individuals gathered before seeking refuge in neighboring countries. This movement resulted in increased vehicular traffic, emergency transport, and heightened commercial activity in certain urban centers, causing an uptick in NO_2 emissions.

El-Geili, situated north of Khartoum, became a key refuge for displaced civilians escaping the conflict in Khartoum and Khartoum North. The increase in emissions in this region can be linked to the expansion of temporary settlements and the continued operation of essential industries, particularly energy and fuel processing facilities. Similarly, Kassala and El-Fashir experienced an uptick in NO_2 emissions due to increased movement of people, vehicles, and humanitarian aid operations. The rise in emissions in these regions suggests that while Khartoum and Khartoum North faced economic collapse, certain areas became hubs for emergency activity, further reflecting the spatial redistribution of economic and social activity in the wake of conflict.

Conclusion

Crises—from COVID-19 to the wars in Ukraine and Sudan—demand rapid, cost-effective decisions precisely when conventional data systems are disrupted, unsafe, or too slow to guide urgent action. In such settings, real-time, spatially resolved information is indispensable. Remote sensing—via satellites and, where feasible, drones or mobile platforms—offers a scalable way to generate timely geospatial intelligence, reveal local heterogeneity, and illuminate how social, demographic, biophysical, and climate factors interact with policy outcomes. This study leverages that capability to track the economic and environmental consequences of Sudan's ongoing conflict using NO_2 concentrations and nightlight intensity.

The spatial and temporal variations in NO_2 concentrations provide valuable insights into how different cities responded to the unfolding conflict. Our findings indicate that the most pronounced declines in NO_2 concentrations and nightlight intensity occurred in Khartoum, Khartoum North, and Omdurman, where the conflict was most severe in its early days. While heavy artillery and ongoing military activity may contribute to emissions, these effects are far outweighed by the collapse of normal economic activity, as evidenced by the sharp declines in both indicators. The closure of factories and manufacturing plants, the suspension of commercial activity, and the large-scale displacement of residents all contributed to the observed reductions in emissions. Additionally, disruptions in intracountry trade, particularly through Khartoum—a key transportation and commercial hub—further contributed to the economic slowdown.

Tragically, the crisis in Khartoum has continued for more than two years, posing severe risks to Sudan's broader economic stability, particularly in the agriculture sector. Many of Sudan's centralized institutions, such as the Agricultural Bank, the Animal Resources Bank, and key government ministries, are located in Khartoum. These institutions play a vital role in supporting agricultural production by facilitating the distribution of inputs, financial services, and infrastructure support. However, the ongoing conflict has severely disrupted these functions, jeopardizing the ability of farmers to access resources needed for the planting season. Moreover, many of Sudan's agricultural processing and value-added industries are concentrated in Khartoum, meaning that food processing activities have largely come to a halt.

Our analysis also indicates that nonconflict regions experienced fewer disruptions in NO_2 emissions and nightlight intensity, suggesting that the economic fallout has been geographically concentrated in specific war-affected areas, at least in the initial months of the conflict. However, in smaller cities and rural areas, the patterns are less clear and sometimes contradictory, as various factors such as wind patterns, seasonal changes, and local industrial activity can influence NO_2 levels.

In the absence of conventional economic data sources—such as national statistics and household surveys—remote sensing provides a crucial tool for monitoring economic activity in conflict zones. Given the impossibility of conducting large-scale ground-based data collection in Sudan at present, satellite-derived indicators can help policymakers, humanitarian organizations, and private sector stakeholders assess the economic impact of the conflict on agriculture, food supply chains, and market stability. These remote-sensing methods significantly enhance our ability to track atmospheric pollution, assess air quality, and understand the interactions between human activity and environmental factors.

Despite these contributions, there are limitations to this study. NO_2 and nightlight data, while effective proxies for economic activity, cannot fully capture the complexity of conflict-related disruptions. For instance, military activity and the use of artillery may temporarily increase emissions, partially offsetting the observed decline in economic activity. Additionally, external environmental factors such as seasonal variability, meteorological influences, and industry-specific emissions fluctuations can introduce variability into NO_2 data. Therefore, while remote sensing provides valuable insights, it should be complemented with other sources of data to build a more comprehensive picture of economic conditions in conflict-affected areas.

Future research should aim to refine and expand this analysis by incorporating additional remote-sensing datasets and ground-truthing data where possible. A promising avenue for further study is the integration of NO_2 and nightlight data with geospatial conflict datasets such as the ACLED (Ali and Ada 2023; Ali 2023), which can provide a more granular understanding of the spatial relationship between armed confrontations and economic disruptions. Additionally, the use of high-resolution satellite imagery and geo-referenced household surveys could offer further insights into localized economic conditions and displacement patterns. These approaches would enable a more nuanced assessment of the war's economic impacts and help guide more effective policy responses and humanitarian interventions.

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