



## Monitoring indicators of economic activity in Sudan amidst ongoing conflict using satellite data

Hala Abushama, Zhe Guo, Khalid Siddig, Oliver Kirui, Kibrom Abay, Liangzhi You

### ABSTRACT

The confrontation in Sudan between the Sudanese Armed Forces (SAF) and Rapid Support Forces (RSF) had persisted for months before escalating into an armed conflict on April 15th, 2023. Besides the severe humanitarian catastrophe, the war has disrupted access to power, water, health services, and banking services while also disrupting access to markets triggering considerable scarcity of goods and services. The conflict has destroyed key infrastructure, constraining domestic and international trade and disrupting production activities and supply chains. In this paper, we utilize satellite data to provide a swift analysis of how the conflict has changed patterns of economic activity, which are bound to have severe implications on food security in Sudan. We also describe how remote sensing and data collection methods can be deployed to monitor economic activities amidst armed conflicts.

Key words: SAF, RSF, conflict, economic activities, NO<sub>2</sub> concentration.

Contents

Abstract ..... 1

Background .....3

the Political Economy of conflicts in Sudan: History renewed.....3

Conflict and Economic Activity .....5

    Satellite data analysis: Tropospheric nitrogen dioxide emissions..... 6

    NO2 concentrations and trends in Sudan ..... 8

    NO<sub>2</sub> changes at the onset of the conflict..... 8

    Town-level NO<sub>2</sub> changes in April 2023.....11

Conclusion..... 13

About the Authors ..... 15

Acknowledgments..... 15

References ..... 15

## BACKGROUND

On April 15<sup>th</sup>, 2023, an armed conflict broke out in Khartoum between the Sudan Armed Forces (SAF) and the Rapid Support Forces (RSF), concluding a 3-year partnership in the Transitional Military Council (TMC). Despite repeated announcements of ceasefire to allow for humanitarian corridors and evacuations, the conflict continues to date.

The ongoing conflict has disrupted economic activity in Khartoum, constrained access to public services, and decimated livelihoods. Media reports indicate that hospitals cannot provide service, banks have closed doors, and access to food is scarce due to the violent conflict. As of May 13<sup>th</sup>, 2023, fewer than 20 percent of health facilities in Khartoum remain fully functional and 60 percent are not operating, severely limiting access to urgent medical services for millions of people (UN-OCHA, 2023a). The displacement of people from conflict areas has put additional pressure on service provision, food resources, public healthcare systems in other states across Sudan. As of May 23<sup>rd</sup>, 2023, over one million people have been internally displaced, while at least 345,000 have crossed into neighboring countries, as a result of the ongoing fighting (ACLED 2023; UN-OCHA, 2023b). Most people who crossed the border went to Egypt (126,000 people) followed by South Sudan (71,000), Chad (60,000), Central African Republic (9,700), and Ethiopia (5,000) according to the UNHCR. The numbers of internal and cross-border displacement are surging by the day (UN-OCHA, 2023b).

The unfolding conflict has major implications on the different domains of the Sudanese economy. Besides the political and humanitarian crises, the scarcity of goods and public services, in addition to reduced purchasing power and surging inflation have collectively contributed to economic contraction (Elamin, 2023). The loss of key infrastructure and disruptions to domestic and international trade have also disrupted production and reduced agricultural activities. This paper provides an early and tentative analysis of how the conflict has changed the patterns of economic activity, which will have severe implications on food security and livelihoods in Sudan. In the absence of detailed and disaggregated survey data on economic activities, remote sensing data and remote data collection methods provide second-best options to inform responses to crises, including humanitarian operations.

## THE POLITICAL ECONOMY OF CONFLICTS IN SUDAN: HISTORY RENEWED

Sudan's political turbulence has had severe implications on agricultural production and food security across the decades. The various forms of conflict in the country's different regions have led to food shortages, agricultural productivity decline, and lowered contributions to GDP growth (Alhelo et al., 2023). Critical infrastructure, such as roads, bridges, irrigation systems, and power supply networks have been severely damaged or destroyed by conflicts. This has hindered transportation, market access, and the delivery of essential services, further impeding economic activities (UNEP, 2007). Prior to the outbreak of the current conflict, estimates indicated that the cost of infrastructure damage caused by conflicts in Sudan exceeds billions of dollars (World Bank, 2020). It is expected that the infrastructure damage and losses due to the current conflict, mostly in the capital Khartoum, will largely amplify these estimates.

The Second Civil War between 1983-2005 between the Sudanese Government and the Sudan People's Liberation Movement/Army (SPLM-A) resulted in significant displacement of people, loss of lives, and destruction of infrastructure in regions such as South Kordofan's Nuba Mountains (Johnson, 2003). It

was estimated that Sudan lost millions of dollars annually in agricultural exports during the war and the conflict led to a disruption in agricultural value chains, exacerbating the food insecurity crisis and impeding economic development (Ahmed, 2006).

Similarly, the Darfur Conflict which arose from complex factors including competition for land and water resources combined with a power struggle built on ethnic tensions (De Waal, 2019), had severe consequences on the welfare of the regions' population. It is estimated that this conflict directly affected around 2.7 million farmers and pastoralists (Flint and De Waal, 2008). Moreover, the disruption in trade routes and insecurity in the region hampered the export of agricultural products, such as livestock, leading to significant losses in revenue (Ebaidalla and Abdalla, 2015).

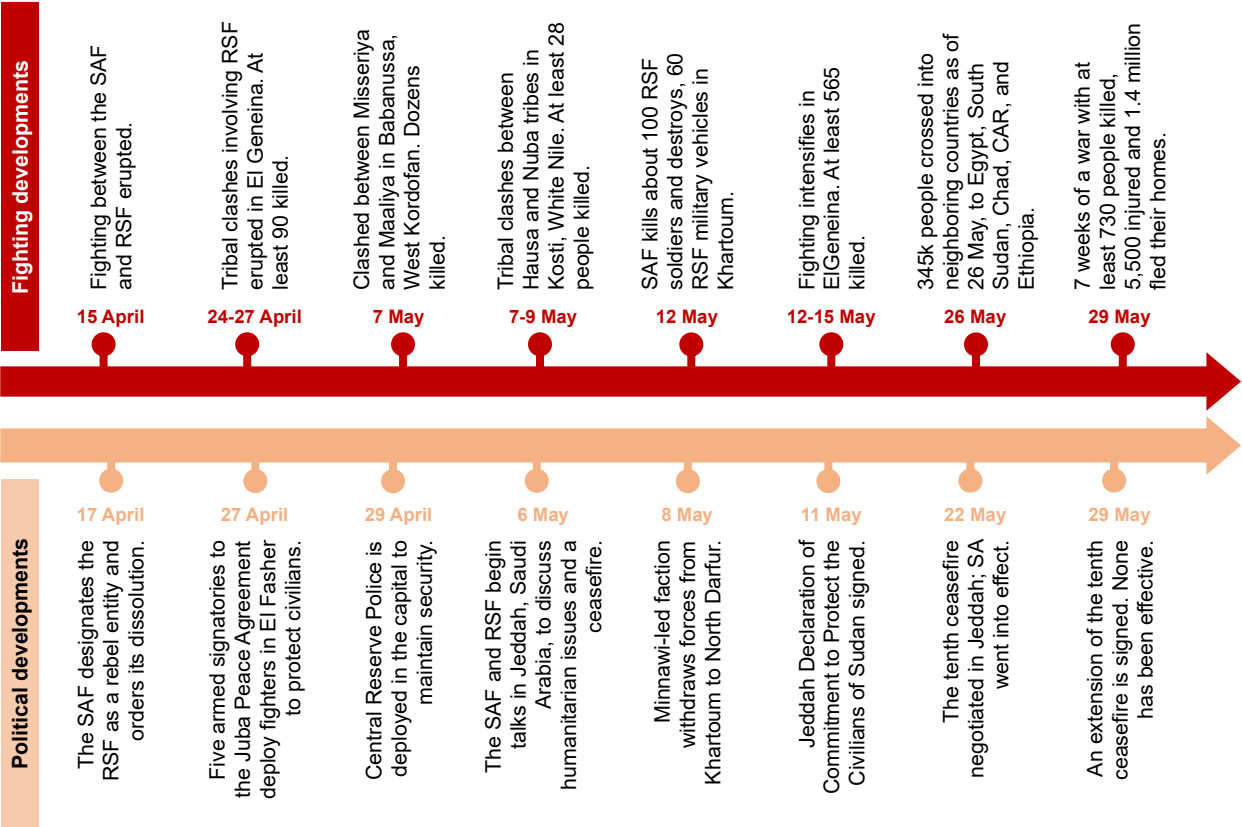
The military in Sudan has historically played a dominant role in economic development (D'Silva et. al, 2022). A combination of factors such as power, economic dominance, and rent-capture drove the gradual ascendance of the military to form a 'military kleptocracy' (Woodward, 2019). Business networks working in tandem with the military were also historically involved in the uneven distribution of wealth forming a system of state clientelism.

Following the December 2018 revolution and the formation of a transitional government in 2019 composed of military and civilian leaders, led by former Prime Minister Abdallah Hamdok, Sudan's hopes of reforming the distribution of political power and economic rents were high. However, due to the underlying tensions between the military and civilian components of the transitional government, the TMC tilted power in their favor during the October 2021 coup. A key element of the tensions was the review of military and paramilitary owned enterprises and their incorporation under the Ministry of Finance and Economic Planning (D'Silva et. al, 2023). Although an overarching framework for power-sharing was signed between civilian bodies and the TMC on December 5<sup>th</sup> 2022, it was not implemented. Without a clear governance framework for the transitional government, and the elimination of the civilian component from power through the coup, the military and paramilitary increasingly found themselves in further disagreement and competition for power and economic dominance in Sudan.

In April 2023, fighting broke out between the SAF under the leadership of General Abdel-Fattah Al-Burhan and his former deputy chief of TMC and leader of the RSF General Mohamed Hamdan Dagalo, also known as Hemedti. Both sides of the conflict have traded accusations about who started the clashes in Khartoum, but the weeks leading up to April 15<sup>th</sup> witnessed preparations and deployment of personnel and heavy equipment into Khartoum by both sides (USIP, 2023).

The warring factions have threatened people's livelihoods and well-being. Although on April 29<sup>th</sup> the Central Reserve Police was deployed for civilian security, looting and terrorization of civilians has continued. Figure 1 highlights the chronology of Sudan's political and fighting developments since April 15<sup>th</sup> until the end of May 2023. Following a week-long negotiation led by Saudi Arabia and The United States, the SAF and RSF signed the Jeddah Declaration of Commitment to Protect the Civilians of Sudan on May 11<sup>th</sup>. Following the signing of the declaration, warring intensified in El-Geneina and Nyala, with at least 565 killed (ACLED, 2023), and the armed conflict continued in Khartoum. On May 22<sup>nd</sup>, 2023, the tenth ceasefire was agreed in Jeddah and on May 29<sup>th</sup> an extension was agreed. However, the violence is likely to persist.

**Figure 1: Chronology of fighting and political events.**



**Source:** Authors' compilation based on ACLED (2023) and data from UN-OCHA (2023b).

The renewed conflict is the first of its kind in Sudan’s history to take place in the capital city (Khartoum), however, the consequences to food insecurity and livelihoods of the SAF and RSF conflict, albeit acute, do not seem different from the previous conflicts.

## CONFLICT AND ECONOMIC ACTIVITY

The nature of conflict varies from context to context; however, a common denominator is the difficulty of monitoring economic challenges at both microeconomic and macroeconomic levels. Due to the outbreak of armed conflicts and the disruption of traditional data collection efforts and methods, quantifying the immediate impacts of an active armed conflict proves difficult. In the absence of conventional survey data, remote sensing tools and remote data collection methods hold significant potential to fill critical data gaps in fragile states (Dabalén et al., 2016; Hoogeveen and Pape, 2020).

Because many public and private institutions have not been operating in Khartoum since April 2023, nation-wide monthly reports have not been published for March and April. Therefore, the availability of data on inflation, exchange rates, and commodity prices has been limited. In addition, the lack of recent disaggregated data in Sudan, necessitates the use of remote sensing methods that can provide indications on the implications on the economy.

Inflation is expected to reach a 3-digit figure by end of May (WFP, 2023). An expected economic contraction is likely, triggered by the disruptions to production (mainly in agriculture and gold mining), trade (mainly imports of food and exports of gold and livestock), job loss (mainly in Khartoum state), investments, and human capital loss as a result of human capital flight. The war has already resulted in decreased availability of essential food items in local markets, causing a surge in food prices. Since April 15<sup>th</sup>, prices of basic commodities such as bottled water, food, and fuel have increased by 40-60 percent in conflict-affected areas (WFP 2023).

Agricultural and industrial production in Khartoum and other conflict areas is expected to drop significantly. The movement of production inputs from Khartoum and Port-Sudan to other areas around the country will be constrained. Smallholder farmers are likely to face limited access to input materials due to the centralized operation of many institutions such as the Agricultural Bank and customs, which cannot operate in Khartoum. Furthermore, in regions like Darfur and Kordofan, where conflict between the SAF and the RSF is escalating, farmers' planting season and pastoralists' grazing routes will be affected.

The private sector has also been hit by the on-going conflict. According to Asharq Alaawsat (2023), Maersk, one of the biggest shipping companies in Sudan has stopped taking bookings until further notice. Without the ability to export gum Arabic, livestock, groundnuts, and other agricultural products, Sudan's trade balance and overall budget deficit will suffer. DAL group, one of the leading companies in the food sector, is not operating because of looting and burning of its factories at the onset of the conflict. Other private sector companies that are major suppliers of food such as SAMIL of the SAY (Salih Abdelrahman Yagoub) Group, which works with WFP and UNICEF to provide school meals for severely malnourished children across Sudan has also been destroyed in Khartoum. According to UN-OCHA (2023a), 24.7 million people need humanitarian assistance due to conflict, which comes on the top of other ongoing food security challenges.

Given the rapid escalation of the ongoing conflict, accurate and reliable information on how economic activity has been impacted in Khartoum and other regions of conflict remains blurred. The next section utilizes remote sensing tools and tropospheric nitrogen dioxide emissions, as a proxy for economic activity in the different regions, to assess how the ongoing conflict impacts Sudan's economy, before and after the eruption of the SAF and RSF conflict.

## **Satellite data analysis: Tropospheric nitrogen dioxide emissions**

By analyzing the spatial and temporal distribution of NO<sub>2</sub>, it becomes possible to identify areas with high levels of pollution, which can be indicative of specific human and economic activities. Densely populated urban areas with heavy traffic and industrial zones often exhibit elevated NO<sub>2</sub> concentrations. By mapping and monitoring these hotspots over time, policymakers and urban planners can make informed decisions regarding land use, transportation infrastructure, and emission control measures to mitigate the impact of human activities on air quality.

The Sentinel-5P OFFL NO<sub>2</sub> product represents a significant advancement in the field of atmospheric monitoring and Earth observation. It is a part of the Sentinel-5 Precursor (S5P) mission, a collaborative effort between the European Space Agency (ESA) and the European Commission. The Sentinel-5P satellite carries the Tropospheric Monitoring Instrument (TROPOMI), a state-of-the-art imaging spectrometer that provides highly accurate and detailed measurements of atmospheric gases, including nitrogen dioxide (NO<sub>2</sub> and NO) (Goldberg et al., 2020).

Nitrogen oxides ( $\text{NO}_2$  and  $\text{NO}$ ) are important trace gases in the Earth's atmosphere, present in both the troposphere and the stratosphere. The Sentinel-5P OFFL  $\text{NO}_2$  product utilizes the data acquired by TROPOMI to generate comprehensive and reliable measurements of  $\text{NO}_2$  levels in the Earth's atmosphere. It offers a range of essential information, including high-resolution maps, near-real-time, vertical profiles, and time series data, enabling scientists, policymakers, and environmental organizations to analyze and address the complex dynamics of  $\text{NO}_2$  pollution.

$\text{NO}_2$  and  $\text{NO}$  are harmful air pollutants primarily emitted from anthropogenic activities including industrial processes, power plants, and vehicles, and natural processes such as wildfires, lightning, and microbiological processes in soils. Monitoring and understanding the distribution and concentration of  $\text{NO}_2$  is crucial for assessing air quality, identifying pollution sources, and implementing effective environmental policies. The Sentinel-5P OFFL  $\text{NO}_2$  product is also valuable for assessing air quality and understanding atmospheric dynamics but also for monitoring human and economic activities that contribute to  $\text{NO}_2$  emissions.

Furthermore, the Sentinel-5P OFFL  $\text{NO}_2$  product enables the near-real-time tracking of changes in  $\text{NO}_2$  emissions associated with specific human and economic activities (e.g., implementation of environmental regulations or conflicts) (Cooper, 2022). In regions affected by armed conflicts or civil unrest, the disruption of industrial activities, the displacement of populations, and the reduced movement of vehicles often lead to a decrease in  $\text{NO}_2$  emissions. By analyzing the spatial and temporal distribution of  $\text{NO}_2$ , this product can provide valuable insights into the extent and duration of conflicts, helping researchers, humanitarian organizations, and policymakers understand the economic consequences of such events. Monitoring the decrease in  $\text{NO}_2$  emissions can be indicative of disrupted economic activities and restricted mobility, contributing to the overall assessment of conflict dynamics. By utilizing the Sentinel-5P OFFL  $\text{NO}_2$  product for conflict monitoring in Sudan, stakeholders can gain a better understanding of the environmental implications of conflicts and make informed decisions to promote sustainable recovery and stability.

In the Sudan case study, we utilize  $\text{NO}_2$  data from two perspectives. Firstly, we create a baseline map of  $\text{NO}_2$  of 2022, indicating the locations of human and economic activity areas. We process the time series of  $\text{NO}_2$  data for Sudan in 2022 and calculate the annual average  $\text{NO}_2$  concentration at pixel level. This helps us assess whether  $\text{NO}_2$  levels can reflect the spatial distribution of human economic centers, serving as a baseline study. Secondly, we analyze the trend of  $\text{NO}_2$  concentration in selected cities both before and after periods of conflict. As the war began on April 15, 2023, we generate a 5-day composite of  $\text{NO}_2$  for April 2023. This allows us to examine the differential trends of  $\text{NO}_2$  in selected cities or regions before and after the conflicts. We calculate the average  $\text{NO}_2$  concentration for each of the 5 days in the entire administrative unit, enabling us to identify variations in trends between cities affected by war and those unaffected. Finally, we create  $\text{NO}_2$  national maps before and after the war to visualize the spatial heterogeneity and patterns.

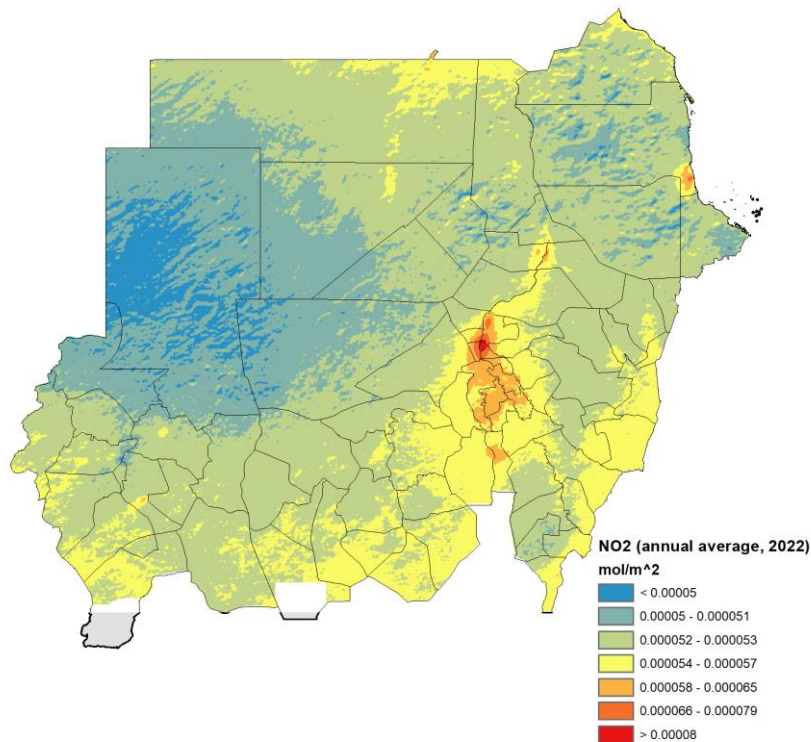
It is worth mentioning that the  $\text{NO}_2$  product primarily serves as a tool for monitoring air quality, and although it can provide insights into human and economic activities, it is more commonly used as an indicator rather than a direct measure of such activities. The utilization of  $\text{NO}_2$  data offers a creative approach to understanding these aspects. However, it is important to consider the limitations and caveats associated with this product. As previously mentioned,  $\text{NO}_2$  levels can be significantly influenced by other factors, including activities such as fertilizer application, as well as climate conditions like rainfall and wind, particularly in regions with low  $\text{NO}_2$  concentrations. The daily, weekly, and even monthly variations in  $\text{NO}_2$  can be heavily influenced by natural processes and cannot correctly capture the dynamics of

human and economic activities on the ground. Therefore, when interpreting the data, it is crucial to account for these external factors that can impact NO<sub>2</sub> concentrations. By acknowledging these caveats and limitations, we can ensure a more comprehensive understanding of the NO<sub>2</sub> data and its implications for monitoring human and economic activities.

## NO<sub>2</sub> concentrations and trends in Sudan

The annual mean TROPOMI-derived ground-level NO<sub>2</sub> concentrations for 2022 provide an initial baseline (Figure 2). With an excellent resolution (about 1 × 1 km<sup>2</sup>) of ground-level NO<sub>2</sub> concentrations, we observe clear heterogeneity across the country. NO<sub>2</sub> concentration is pronounced over urban areas resulting from industrial activities and heavy vehicle movement as opposed to rural areas with less emissions.

**Figure 2:** Average of NO<sub>2</sub> concentration (mol/m<sup>2</sup>) in 2022.



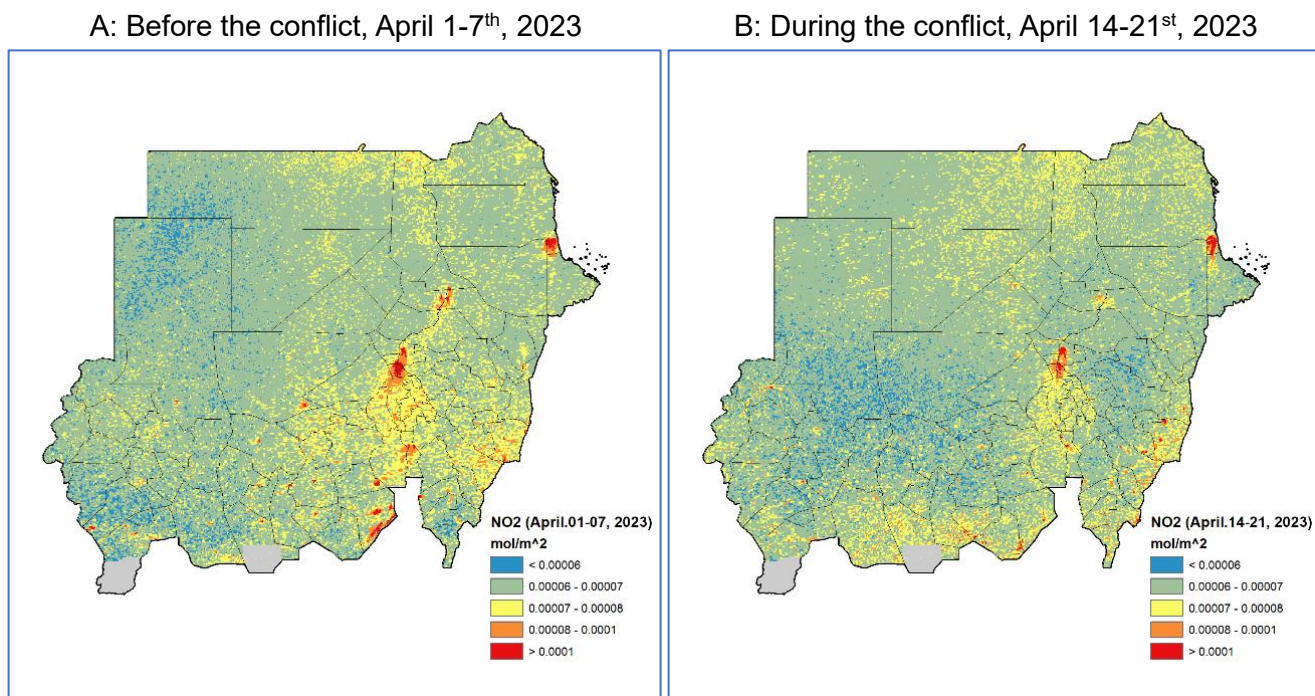
**Source:** Authors' depiction based on Sentinel-5P OFFL TROPOMI-derived NO<sub>2</sub>

## NO<sub>2</sub> changes at the onset of the conflict

The study looks at different regions in Sudan, in conflict zones and those not in conflict zones, to depict NO<sub>2</sub> changes and to assess the implications of the ensuing conflicts on economic activities. The intensity of the confrontation was the highest in Khartoum State, especially in Khartoum City where the military headquarters and many public institutions are based. The intensity of confrontation is also evident, albeit to a lesser extent, in the other twin cities of Omdurman and Khartoum North.

In Figure 3 we compare NO<sub>2</sub> levels in Sudan before the war (i.e., panel A: during April 1-7, 2023) and after the eruption of the conflict (i.e., panel B: during April 14-21<sup>st</sup>, 2023). The NO<sub>2</sub> concentration on panel A, while showing higher intensity on the capital state and Port Sudan area spread widely in most of the central, eastern, and southern regions of the country. This concentration is much more muted in panel B, especially in the Atbara area of the River Nile state, El Gadarif State, El Gezira state and the central regions of the country.

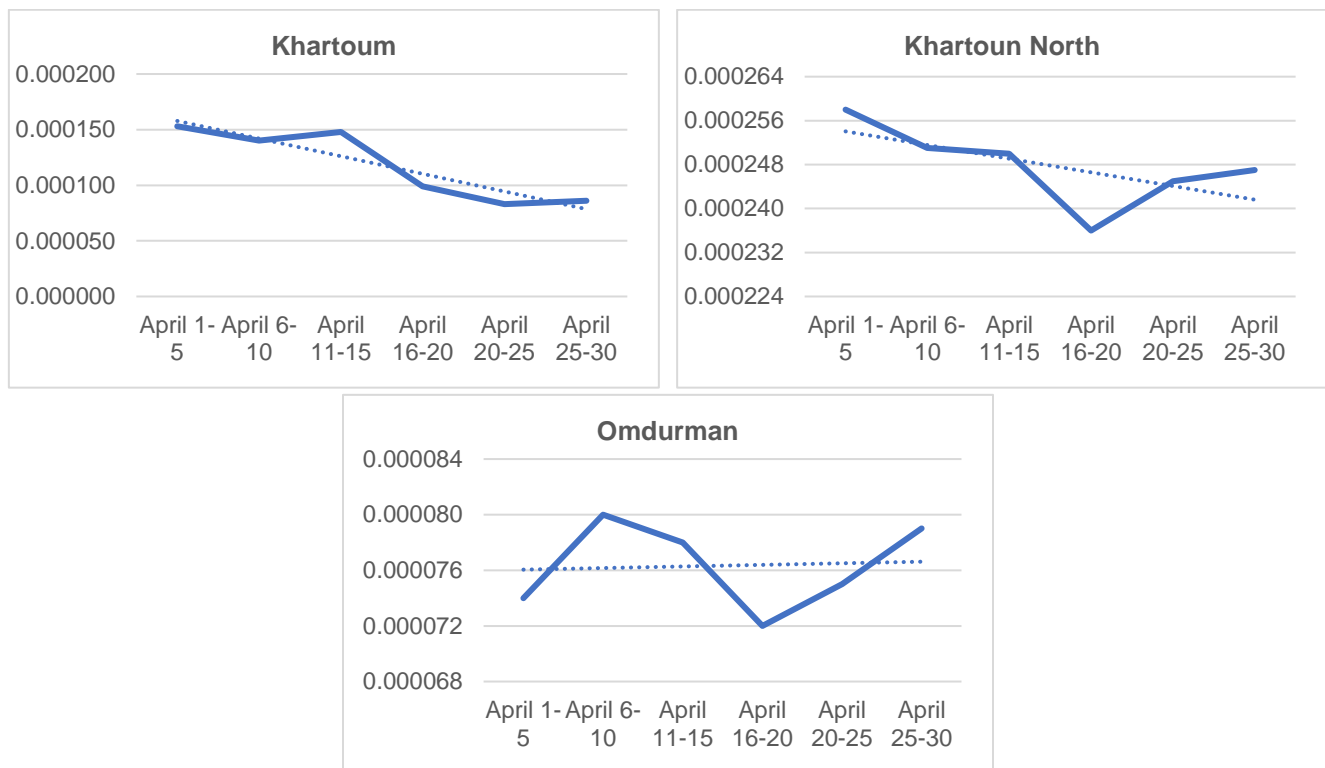
**Figure 3:** NO<sub>2</sub> levels (mol/m<sup>2</sup>) in Sudan before and during conflict



**Source:** Authors' depiction based on Sentinel-5P OFFL TROPOMI-derived NO<sub>2</sub>

The following Figure 4 and Figure 5 zoom in slightly further and show the mean ground-level NO<sub>2</sub> concentrations derived from TROPOMI observations for the entire month of April 2023 for selected regions experiencing conflict and those not experiencing conflict, respectively. The data shows that the NO<sub>2</sub> changes in around greater Khartoum are quite evident. The trend of NO<sub>2</sub> concentrations is on a decline in the two regions of Khartoum (Khartoum and Khartoum North) soon after the conflict erupted on April 15, 2023. The abrupt stoppage of movement of people in and around Khartoum implies reduced NO<sub>2</sub> emissions and reduced economic activities. While the epicenter of the conflict is in Khartoum, many people escaped or sought refuge in Omdurman and the northern areas of Khartoum North. This may explain the relatively flat trends in NO<sub>2</sub> concentration in Omdurman and Khartoum North towards the end of April 2023 (Figure 4).

**Figure 4:** NO<sub>2</sub> levels (mol/m<sup>2</sup>) in the trio Khartoum cities experiencing conflict.

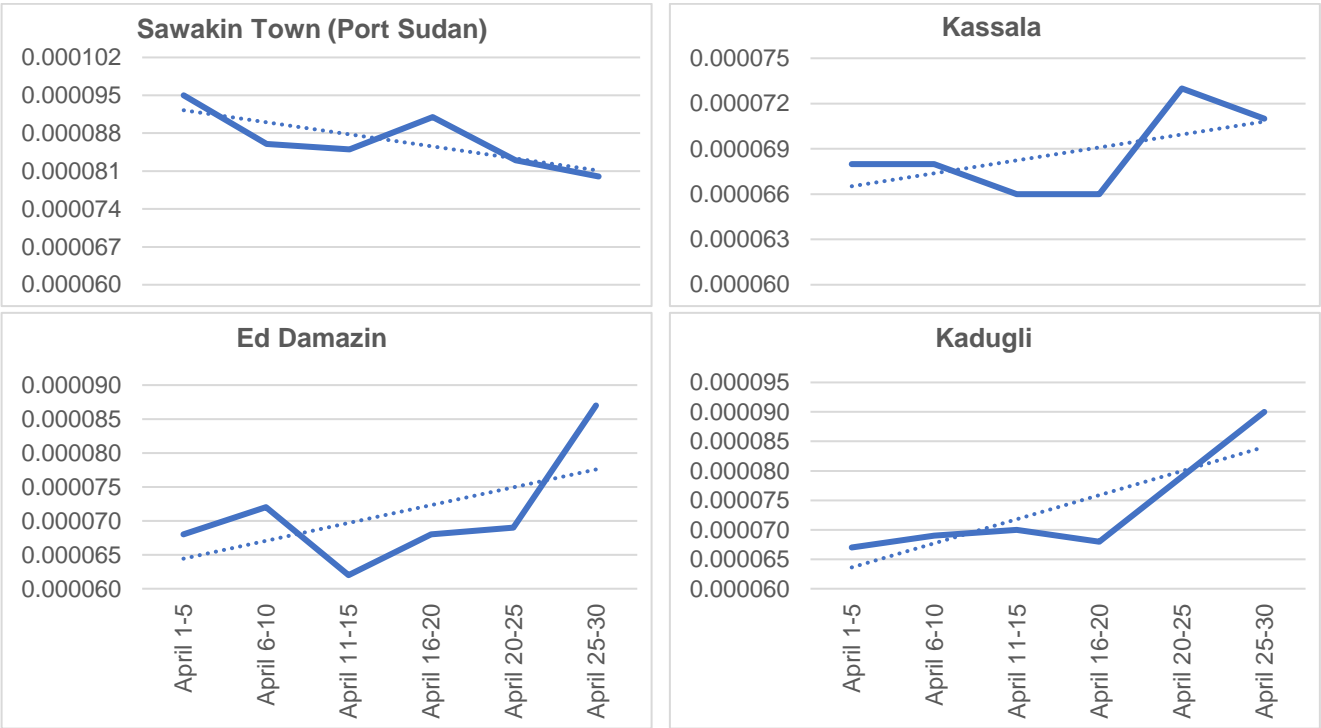


**Source:** Authors' depiction based on Sentinel-5P OFFL TROPOMI-derived NO<sub>2</sub>

On the other hand, the NO<sub>2</sub> concentration in regions less affected by conflict compared to Khartoum state, namely Ed Damazin, Kadugli and Kassala showed positive upward trends in the entire period of April (Figure 5). These areas are farther from the conflict zone and experienced relatively more movement than usual. Most people that finally escaped out of Khartoum headed to safe locations like Kassala and north toward Port Sudan in the Red Sea State, explaining the increase in NO<sub>2</sub> emissions in the weeks of April 16-30, following the breakout of the conflict in Khartoum. These cities are not necessarily final destinations of the people fleeing the war, but instead transitional locations before further movement across borders to neighboring countries (e.g., to Saudi Arabia via Kassala- Port Sudan route or to South

Sudan via Kadugli or Ed Damzeen route depending on where the journey starts).<sup>1</sup> The escalation of the conflict and relative reduction of economic activities in Khartoum also saw reduced movement of goods from and to Port Sudan (imports and exports). This may explain the decline in NO<sub>2</sub> concentration in Sawakin though it was farther away from Khartoum. Port Sudan is a significant point of entry for imports and point exit for exports.

**Figure 5:** NO<sub>2</sub> levels (mol/m<sup>2</sup>) in the other regions of Sudan not experiencing conflict.



Source: Authors' depiction based on Sentinel-5P OFFL TROPOMI-derived NO<sub>2</sub>

### Town-level NO<sub>2</sub> changes in April 2023

The fine resolution of the satellite-derived ground-level NO<sub>2</sub> dataset enables the assessment of larger changes in NO<sub>2</sub> concentrations at smaller scale. We report TROPOMI-observed weekly mean ground-level NO<sub>2</sub> for the week of April 1-7, 2023 (before the war) and week of April 14-21, 2023 (the first week of the war), for selected cities including conflict and non-conflict affected (Table 1). We also calculate the percentage changes in NO<sub>2</sub> concentration of the first week of the war from the first week of April (before the war). All the regions in conflict areas experienced a reduction in NO<sub>2</sub> except in El Geili, in the northern part of Khartoum state and Sawakin in the Red Sea state. In El Geili, this relates to the major refinery of oil, which has been kept away from the confrontations due to its significance for the economy and the movement of people out of Khartoum and central Khartoum north area seeking refuge in the El Geili surroundings. Sawakin was not affected in the first week of the war because of its location far away from the initial conflict zone. The highest reductions were observed in Khartoum (34 percent), and Khartoum

<sup>1</sup> Most of the people internally displaced have taken refuge in West Darfur (24 percent), White Nile (20 percent), River Nile (16 percent) and Northern (14 percent) states (UN-OCHA, 2023b).

North (18 percent) followed by El Fashir (6 percent) and Es Sileit (4 percent), where both witnessed confrontations during the first week of the war due to the existence of RSF military bases, targeted by the SAF. On the other hand, all regions not in conflict zones had little change or a slight increase in NO<sub>2</sub> concentration, with the increase usually associated with hosting more people fleeing the war.

**Table 1: NO<sub>2</sub> Concentration (mol/m<sup>2</sup>) and their changes in selected cities of Sudan in April 2023**

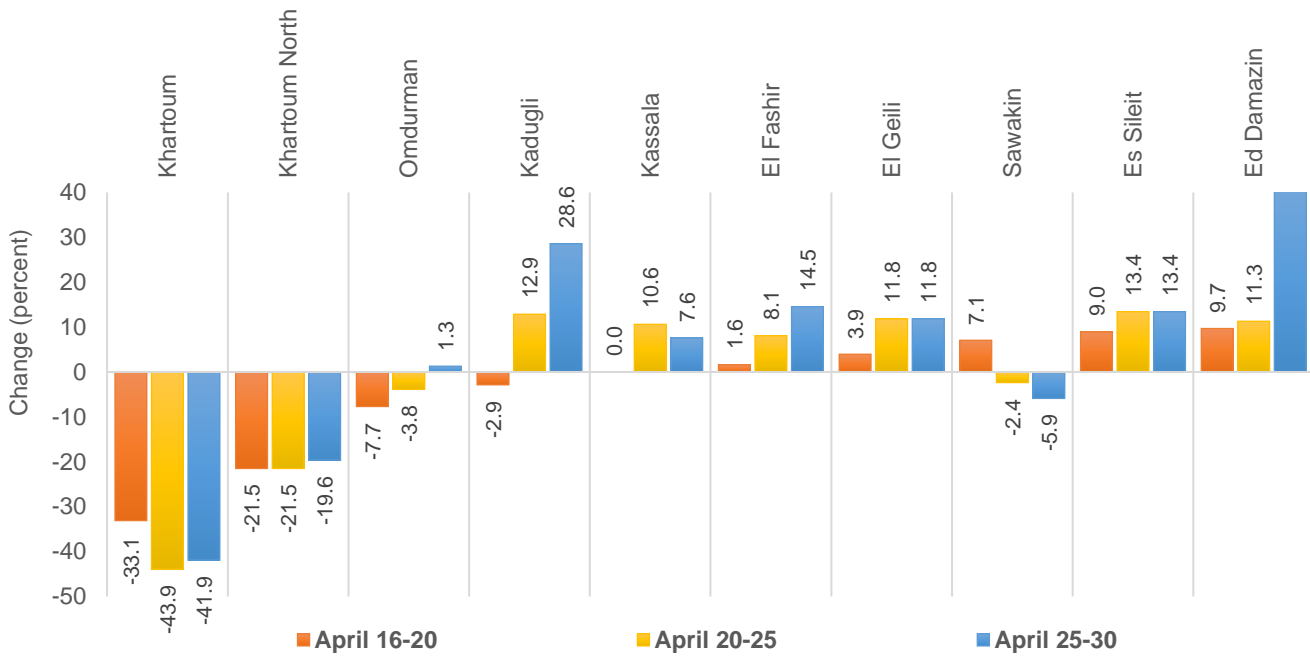
Cities	April 1-7,2023 (mol/m <sup>2</sup> )	April 14-21,2023 (mol/m <sup>2</sup> )	Change (percent)	Conflict?
<b>Khartoum</b>	0.000153	0.000101	-33.99	Yes
<b>El Geili</b>	0.000079	0.000081	2.53	Yes
<b>Es Sileit</b>	0.000076	0.000073	-3.95	Yes
<b>Khartoum North</b>	0.000103	0.000085	-17.48	Yes
<b>Omdurman</b>	0.000067	0.000067	0.00	Yes
<b>Sawakin</b>	0.000097	0.000099	2.06	No
<b>Kassala</b>	0.006800	0.006800	0.00	No
<b>El Fashir</b>	0.000068	0.000064	-5.88	No
<b>Kadugli</b>	0.000069	0.000069	0.00	No
<b>Ed Damazin</b>	0.000068	0.000068	0.00	No

Source: Authors' calculation based on Sentinel-5P OFFL TROPOMI-derived NO<sub>2</sub> data.

To assess the impact on the different cities during the first weeks of the war, we calculated the percentage change in NO<sub>2</sub> concentration of three periods (Figure 6), namely, April 16-20, April 20-25, and April 25-30, 2023, from the immediate five days before the war (April 10-15, 2023). In Khartoum city, the concentration decreased by 33 percent, 44 percent, and 42 percent in the three periods, respectively while it decreased by between 20 percent and 22 percent, 22 percent, and 20 percent in Khartoum North. These two cities are directly affected by the war during this period and the reductions are associated by the movement of the civilians out of the cities and the disruption of the factories (mainly in Khartoum North area).

The case of Sawakin city is interesting because it shows that the port continued operation in the first period (the first five days of the conflict) because the city is far away from the conflict zone. However, the operation of the port declined rapidly afterward as the connection of the port to other major trade cities was disrupted by the war. The NO<sub>2</sub> concentration in most of the other cities increased gradually through the three period because they are either recipients of internally displaced people from other regions of the country (e.g., El Gaili and Kassala) or transitions to other locations inside the country or outside the country (e.g., Elfashir, Ed Damazeen and Kadugli).

**Figure 6:** Changes in NO<sub>2</sub> concentration (mol/m<sup>2</sup>) of three periods after the conflict compared to the April 11-15 period.



Source: Authors' calculation based on Sentinel-5P OFFL TROPOMI-derived NO<sub>2</sub> data.

## CONCLUSION

This paper investigates the recent political developments in Sudan, leading up to the armed conflict between the SAF and the RSF, and their implications on economic activity. The conflict has exacerbated the economic and political crisis in Sudan and, because of its centralized location in Khartoum, government entities, private sector companies, and public services have been impacted. This rapid analysis aims to inform domestic and international stakeholders, including those related to humanitarian operations, and paves the way for deeper understanding of the sectoral implications of the armed conflict in Sudan.

Monitoring economic activity amidst an armed conflict is challenging because conflicts disrupt traditional data collection efforts. But the advent of remote sensing tools and remote data collection methods provide the second-best options. We utilize NO<sub>2</sub> data to create a baseline map for 2022, indicating the locations of human and economic activity. We then analyze the trends of NO<sub>2</sub> concentration in selected cities immediately before the conflict to generate a 5-day composite of NO<sub>2</sub> for April 2023 and compare this to a similar 5-day composite of NO<sub>2</sub> in a series of 5 day periods immediately following the onset of the war to allow us to examine the differential trends of NO<sub>2</sub> in selected cities or regions before and after the conflict. Finally, we create NO<sub>2</sub> national maps before and after the war to visualize the spatial heterogeneity and patterns.

The preliminary results analyzing NO<sub>2</sub> emissions show a decrease of activity in Khartoum, Khartoum North, and Omdurman indicating the movement of citizens and the ceasing of economic activity associated with the closure of factories and commercial sectors. Khartoum is also the host of many public and private institutions including the banking sector and government as well as private sector institutions

involved in the agricultural sector posing a threat to food security in the future if planting or food processing is limited.

Port Sudan, Sawakin and Kassala witnessed surges in NO<sub>2</sub> emissions, indicating the possibility of being key destinations for internally displaced citizens, as well as a base for shifting economic activity. Ed Damazin in Blue Nile, and Kadugli in South Kordofan also witnessed an increase in NO<sub>2</sub> emissions at the onset of the conflict, albeit to a lower extent than the eastern states, indicating the possible influx of migrants, many of which may be destined for South Sudan. However, according to WFP, supplies of food are running low in South Kordofan while prices have increased by five-fold compared to April (WFP, 2023). Other non-conflict regions show less change in NO<sub>2</sub> concentrations. For small cities, the pattern is less clear and sometimes contradictory due to various factors that can affect NO<sub>2</sub>, such as wind and temperature.

In the absence of conventional data sources due to the armed conflict, remote sensing data provides new opportunities to understand the trajectory of economic activity in Sudan to inform policymakers, private sector, and humanitarian aid workers of the potential impact of the conflict on agriculture, food value chains, and food insecurity.

---

## ABOUT THE AUTHORS

**Hala Abushama** is a Research Assistant in IFPRI's Development Strategy Governance Unit, Khartoum, Sudan. **Zhe Guo** is Senior GIS Coordinator in IFPRI's Foresight and Policy Modeling Unit. **Khalid Siddig** is a Senior Research Fellow and Program Leader in IFPRI's Development Strategy Governance Unit, Khartoum, Sudan. **Oliver Kirui** is a Research Fellow in IFPRI's Development Strategy Governance Unit, Khartoum, Sudan. **Kibrom Abay** is a Senior Research Fellow and Program Leader in IFPRI's Development Strategy Governance Unit, Cairo, Egypt. **Liangzhi You** is Senior Research Fellow in IFPRI's Foresight and Policy Modeling Unit.

---

## ACKNOWLEDGMENTS

This paper was prepared with the gracious financial support of the United States Agency for International Development (USAID).

---

## REFERENCES

- ACLED (Armed Conflict Location & Event Data Project). (2023). Situation Update | May 2023. Sudan: Fighting Rages Amid Ceasefire Talks. Accessed on May 28, 2023 from: [Sudan Situation Update: May 2023 | Fighting Rages Amid Ceasefire Talks \(acleddata.com\)](https://acleddata.com/sudan-situation-update-may-2023-fighting-rages-amid-ceasefire-talks/)
- Ahmad, A. M. (2006). Understanding the Crisis in Darfur: Listening to Sudanese Voices. University of Bergen, 2006.
- Ahmed, M. O. M. and Siddig, K. (2023). Quarterly bulletin on food price dynamics, inflation, and the food security situation in Sudan: 2021Q1-2022Q4 et al, 2023. [Quarterly bulletin on food price dynamics, inflation, and the food security situation in Sudan: 2021Q1- 2022Q4 | IFPRI : International Food Policy Research Institute](https://www.ifpri.org/publication/quarterly-bulletin-on-food-price-dynamics-inflation-and-the-food-security-situation-in-sudan-2021q1-2022q4)
- Alhelo, A., Siddig, K., and Kirui, O. K. (2023). The Architecture of the Sudanese Agricultural Sector and its Contribution to the Economy between 1990 and 2021. IFPRI Discussion Paper May 2023, forthcoming.
- Asharq Al-Awsat. (2023). Sudan Conflict Deals New Blow to Stagnant Economy. <https://english.aawsat.com/home/article/4310406/sudan-conflict-deals-new-blow-stagnant-economy>
- Brachet, E. (2023). Sudan: Region's political Islamist movement plays key role in conflict, Le Monde, May 3, 2023. [https://www.lemonde.fr/en/le-monde-africa/article/2023/05/03/sudan-region-s-political-islamist-movement-plays-key-role-in-conflict\\_6025334\\_124.html](https://www.lemonde.fr/en/le-monde-africa/article/2023/05/03/sudan-region-s-political-islamist-movement-plays-key-role-in-conflict_6025334_124.html)
- Cooper, M.J., Martin, R.V., Hammer, M.S., Hammer, M.S., Levelt, P.F., Veefkind, P., Lamsal, L.N., Krotkov, N.A., Brook, J.R., Mclinden, C.A. (2022) Global fine-scale changes in ambient NO<sub>2</sub> during COVID-19 lockdowns. Nature 601, 380–387. <https://doi.org/10.1038/s41586-021-04229-0>
- Dabalen, A., A. Etang, J. Hoogeveen, E. Mushi, Y. Schipper, and J. von Engelhardt. (2016). Mobile Phone Panel Surveys in Developing Countries: A Practical Guide for Microdata Collection. Directions in Development. Washington, DC: World Bank. <https://doi.org/10.1016/j.dindev.2016.03.001>
- De Waal, A. (2019). Sudan: a political marketplace framework analysis. Occasional Papers (19). World Peace Foundation, Somerville, MA. [De Waal Sudan a political marketplace analysis published.pdf \(lse.ac.uk\)](https://www.wpf.org/sites/default/files/2019-08/De%20Waal%20Sudan%20a%20political%20marketplace%20analysis%20published.pdf)
- D'Silva, B.C, El-Battahani, A., and Hassan, R.M. (2022). Evolution of Agricultural State-Owned Enterprises (SOEs) in Sudan: A Case Study of Greater Khartoum. IFPRI (unpublished)
- D'Silva, B.C, Hassan, R.M., Hutur, A., Ibrahim, S., Abushama, H., Siddig, K., and Kirui, O. (2023). Political Constraint and Opportunities for Agricultural Investment in Sudan. IFPRI Policy Note (4). Sudan Strategy Support Program
- Ebaidalla, M. E. and Abdalla, A. A. (2015). Performance of Sudanese Agricultural Exports: A Gravity Model Analysis. University of Khartoum. Available from: [https://www.researchgate.net/publication/279439829\\_Performance\\_of\\_Sudanese\\_Agricultural\\_Exports\\_A\\_Gravity\\_Model\\_Analysis#fullTextFileContent](https://www.researchgate.net/publication/279439829_Performance_of_Sudanese_Agricultural_Exports_A_Gravity_Model_Analysis#fullTextFileContent) [accessed May 30, 2023].
- Elamin, N. (2023). The Effect of Sudan's War on the Economy: A preliminary assessment.
- Flint, J., and de Waal, A. (2008). Darfur: A new history of a long war. Bloomsbury Publishing, 2008 ISBN: 1848133413, 9781848133419.
- FSI. (2023). Fragile States Index. [Country Dashboard | Fragile States Index](https://www.fsi.csis.org/)
- Goldberg, D. L., Anenberg, S., Moheg, A., Lu, Z. & Streets, D. G. (2020). TROPOMI NO<sub>2</sub> in the United States: a detailed look at the annual averages, weekly cycles, effects of temperature, and correlation with PM<sub>2.5</sub>. Preprint at <https://doi.org/10.1002/2020gl000000>
- Hoogeveen, J. and Pape, U. (2020). Data Collection in Fragile States: Innovations from Africa and Beyond. Cham, Switzerland: Palgrave Macmillan. World Bank. <https://openknowledge.worldbank.org/handle/10986/32576>

- Johnson, D. (2003). The root causes of Sudan's civil wars. Indiana University Press.
- McGregor, A. (2023). Gold, Arms, and Islam: Understanding the Conflict in Sudan. The Jameson Foundation. <https://jamestown.org/program/gold-arms-and-islam-understanding-the-conflict-in-sudan/>
- UNEP. (2007). Sudan: Post-conflict environmental assessment. United Nations Environment Programme. [Sudan: Post-conflict environmental assessment - Sudan | ReliefWeb](#)
- UN-OCHA. (2023a). Revised humanitarian response plan, Sudan. Humanitarian programme cycle 2023, revision issued on 17 May 2023. [revised\\_2023\\_hrp\\_sudan\\_final\\_0.pdf \(fscluster.org\)](#)
- UN-OCHA. (2023b). Sudan: Clashes between SAF and RSF - Flash Update No. 14 (28 May 2023). [Sudan: Clashes between SAF and RSF - Flash Update No. 14 \(28 May 2023\) \[EN/AR\] - Sudan | ReliefWeb](#)
- UN-OCHA. (2022). Sudan: Humanitarian Needs Overview. United Nations Office for the Coordination of Humanitarian Affairs.
- USIP. (2023). What's Behind the Fighting in Sudan? The ongoing confrontation between the military and Rapid Support Forces undermines stability in Sudan and the Horn of Africa.
- WFP. (2023). WFP Market Monitor- Sudan. April 2023.
- Woodward, P. (2019). Sudan: Soldiers and Civilians, 1958-2019 manuscript. Oxford Encyclopedia of the Military in Politics. Oxford University Press.
- World Bank. (2020). Sudan: A Strategy for Rebuilding Inclusive and Sustainable Growth. World Bank Group.

The Sudan Strategy Support Program (SSSP) is managed by the International Food Policy Research Institute (IFPRI) and is financially supported by the United States Agency for International Development (USAID). This publication has been prepared as an output of the SSSP and has not been independently peer-reviewed. Any opinions expressed here belong to the author(s) and are not necessarily representative of or endorsed by IFPRI.

## INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

*A world free of hunger and malnutrition*

IFPRI is a CGIAR Research Center

IFPRI Sudan, Arab Organization for Agricultural Development (AOAD), 7th Amarat Street | P.O. Box 474 – 11111 | Khartoum, Sudan

| Email: [ifpri-sudan@cgiar.org](mailto:ifpri-sudan@cgiar.org) | <https://sudan.ifpri.info/>

© 2023, copyright remains with the author(s). All rights reserved.