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TROPOMI-derived NO₂ emissions from copper/cobalt mining and other industrial activities in the Copperbelt (DRC and Zambia)

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Key Points:

- We quantified annual 2019-2022 TROPOMI-derived NO₂ emissions from six point sources in the Copperbelt, despite high background emissions.
- Annual TROPOMI-derived NO₂ emissions from these point sources are strongly correlated with annual mine/oil refinery production.
- Lack of elevated SO₂ at these point sources is consistent with SO₂ capture and production of sulfuric acid, a profitable byproduct.

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Abstract

We have analyzed TROPOMI data over the Copperbelt mining region (Democratic Republic of Congo and Zambia). Despite high background values, we find that annual 2019-2022 means of TROPOMI NO₂ show local enhancements consistent with six point sources (mines and cities) where high-emission industrial activities take place. We have quantified annual NO₂ emissions for the six sources, identified temporal trends in these emissions, and found strong correlations with mine/refinery production data. CAMS-GLOBANT v5 inventory emissions are lower than TROPOMI-derived emissions by 61-96 % and lack the temporal trends observed in TROPOMI and mine/oil refinery production. Lack of TROPOMI SO₂ enhancements over the point sources analyzed indicates SO₂ capture and transformation into sulfuric acid, a profitable byproduct. These results demonstrate the potential for satellite monitoring of mining/oil refining activity which impacts the air quality of local communities. This is particularly important for Africa, where mining is increasing aggressively.

Plain Language Summary

We show that air pollution from copper/cobalt mines and oil refineries can be identified and measured from satellite, even in the presence of high background pollution from biomass burning and other sources; our findings may apply as well to other industries that consume large quantities of fossil fuels. This is important for monitoring the air quality of local communities, particularly when these industrial activities take place in close proximity to population centers, as is the case in the Copperbelt and, in general, in other African regions where mining and related industrial activities proliferate without sufficient air quality monitoring. Additionally, we show for the first time that the amount of air pollution measured by TROPOMI is strongly correlated with mine/refinery production. Studies like this can be used to estimate mine/refinery production before companies release their annual reports or (as is the case with non-publicly traded companies) in the absence of such reports. Insufficient emissions from mines claiming high production may be indicative of production from a different source. Thus, this method may help improve the traceability of minerals extracted in conflict areas and smuggled into the global supply chain despite existing traceability and tagging schemes.

1 Introduction

The Copperbelt, a mining region straddling the DRC (Democratic Republic of Congo) and Zambia, is currently of great strategic interest because it is the world's largest cobalt producer and holds almost half of the world reserves (Shedd, 2022). Cobalt production in the Copperbelt (mostly in the DRC) has increased ~600% between 1990 and 2021 (U.S. Bureau of Mines, 1993; Shedd, 2022), driven by its use in lithium-ion batteries which power mobile phones, laptops, and electric cars. Access to the Copperbelt's cobalt is becoming a matter of national and global energy security (Gulley, 2022). Cobalt is, however, a byproduct of copper mining; copper is the main ore (by volume) extracted in the Copperbelt. Previous studies have documented the impact of cobalt and/or copper mining in the region's soils and water (Atibu et al., 2016), land use (Mwitwa et al., 2012), and neonatal health (Kayembe-Kitenge et al., 2019; Van Brusselen et al., 2020). The impact on local air quality remained unknown. Here we quantify the effect of increasing mining activity on the air quality of this region using TROPOMI (TROPOspheric Monitoring Instrument) satellite measurements (Veefkind et al., 2012) of NO₂ (nitrogen dioxide); TROPOMI SO₂ (sulfur dioxide) is also analyzed. Both gases are atmospheric pollutants (World Health Organization, 2021) relevant to air quality monitoring and forecasting. They are also considered short-lived climate forcers, important for understanding climate (Myhre et al., 2013).

72 NO_x ($\text{NO}_2 + \text{NO}$, two species closely intertwined by oxidation and reduction re-
 73 actions), has both anthropogenic (fossil fuel combustion, biomass burning) and natural
 74 (microbial activity in soils, lightning, wildfires) sources. Mining-related NO_x is produced
 75 by high-temperature combustion of fuel used by trucks and other heavy machinery as
 76 well as by electric generators. The main sink of NO_x is the hydroxyl radical (OH), with
 77 which it reacts within hours in the presence of light. NO_x has a negative impact on air
 78 quality, both directly and as a precursor to tropospheric ozone and particulate matter.
 79 It is damaging to human health (affecting mostly the respiratory system) and crops, and
 80 contributes to the formation of smog and acid rain. Hereafter we discuss NO_2 , the NO_x
 81 component measurable from satellite.

82 Measuring global and regional NO_2 was made possible by satellite instruments such
 83 as GOME (Global Ozone Monitoring Experiment), SCIAMACHY (SCanning Imaging
 84 Absorption SpectroMeter for Atmospheric CHartographY), OMI (Ozone Monitoring In-
 85 strument), and GOME-2, (Leue et al., 2001; Richter et al., 2005; Beirle et al., 2011; Richter
 86 et al., 2011). Labzovskii et al. (2022) reported regional-scale correlation between OMI
 87 NO_2 column values from heavy industry, including mining, and a coal production inter-
 88 annual variability index for the Siberian Kuzbass Basin. Thanks to its higher spatial res-
 89 olution, TROPOMI allows for the measurement of NO_2 over smaller domains such as
 90 gas and oil fields (Dix et al., 2022), cities (Goldberg et al., 2019; Pommier, 2022; de Foy
 91 & Schauer, 2022), and power plants (Beirle et al., 2019, 2021; Goldberg et al., 2019; Dix
 92 et al., 2022; de Foy & Schauer, 2022).

93 SO_2 results from both anthropogenic (e.g., coal combustion, smelting of sulfur-rich
 94 ores) and natural (volcanism, marine biological processes) sources. It contributes to acid
 95 rain and particle formation. Exposure to SO_2 is harmful to human health, damages fo-
 96 liage, and impedes plant growth. Previous studies showed that SO_2 emissions could be
 97 estimated using satellite data from TOMS (Total Ozone Mapping Spectrometer), GOME,
 98 OMI, SCIAMACHY, and OMPS (Ozone Mapping and Profiler Suite) (Krueger, 1983;
 99 Carn et al., 2007; V. E. Fioletov et al., 2013; Zhang et al., 2017). V. Fioletov et al. (2020,
 100 2023) reported TROPOMI-based emission estimates of SO_2 from power plants, volca-
 101 noes, oil and gas fields, and smelters.

102 We show that copper/cobalt mining-related activities, among others, can be iden-
 103 tified and their NO_2 emissions quantified based on TROPOMI data even in the presence
 104 of high background values from biomass burning and other sources (BIRA-IASB, 2021).
 105 Additionally, we identify inter-annual trends in TROPOMI-derived NO_2 emissions that
 106 are strongly correlated with mining and oil refinery production. Next we describe the
 107 datasets (Sect. 2) and methodology (Sect. 3) used in this study, we present our results
 108 (Sect. 4), and discuss their relevance (Sect. 5). Conclusions are offered in Sect. 6.

109 2 Datasets

110 TROPOMI, onboard the European Space Agency's Sentinel-5 Precursor satellite
 111 (Veefkind et al., 2012), provides quasi-global daily coverage at high spatial resolution (3.5
 112 $\times 5.5 \text{ km}^2$ for our species of interest). This is a nadir-viewing imaging spectrometer in
 113 a sun-synchronous orbit at 824 km of altitude, with 13:30 LST Equator-crossing time,
 114 and 2600 km swath width. TROPOMI measures radiances in the ultraviolet, visible, and
 115 reflected infrared, from which concentrations of trace gases as well as cloud and aerosol
 116 properties are derived. Here we focus on TROPOMI measurements of tropospheric NO_2
 117 and SO_2 , two pollutants produced by mining-related activities. NO_2 is retrieved from
 118 TROPOMI radiance measurements in the visible portion of the spectrum (400-496 nm)
 119 (van Geffen et al., 2020; H. J. Eskes & Eichmann, 2021; H. Eskes et al., 2022). We used
 120 daily TROPOMI NO_2 tropospheric column data from version 2 for the period between
 121 1 January 2019 and 31 December 2022. We also analyzed TROPOMI SO_2 data retrieved
 122 with the Covariance-Based Retrieval Algorithm (COBRA, Theys et al. (2021)) from ultraviolet-

123 visible radiances (310.5-326 nm) (Theys, 2022) for the 1 January 2019 - 31 July 2022 pe-
124 riod; more recent data were unavailable at the time of writing.

125 Meteorological information needed to derive emissions from TROPOMI NO₂ VCD
126 (vertical column density) was obtained from reanalysis data. By combining measurements
127 and model results, reanalyses datasets provide consistent and gapless global coverage of
128 essential climate variables. We used hourly ERA5 (ECMWF Reanalysis v5) data (Hersbach
129 et al., 2020) provided at 0.25° x 0.25° resolution and generated by the Copernicus Cli-
130 mate Change Service at the European Center for Medium-Range Weather Forecasts.

131 Due to the unavailability of ground measurements, we compared inventory data to TROPOMI-
derived NO₂ emissions. Emission inventories are compilations of amounts of air pollutants released into the
atmosphere, segregated by source and time period. We used 2019-2021 data from the CAMS-GLOB-ANT
(Copernicus Atmosphere Monitoring Service Global Anthropogenic) emissions inventory version 5, an
extension of version 4.2 (Granier et al., 2019). Inventory emissions for 2022 were unavailable at the time of
writing. We focused on monthly NO_x emissions, provided at 0.1° x 0.1° resolution.

138 Mine production data were obtained from the annual reports of publicly traded min-
139 ing companies; these reports are mandated by official regulatory bodies such as the Se-
140 curities and Exchange Commission in the United States and the Securities and Futures
141 Commission in Hong Kong. Private mining companies are not required to disclose their
142 production data. The specifics of the information available in these reports varies greatly.

143 **3 Methodology**

144 To identify potential emission point sources such as mines, we produced annual means
145 from daily TROPOMI NO₂ VCD for the Copperbelt study area (-10.5°N to -13.5°N, 24.5°E
146 to 29.5°E). Temporal averaging enhances the signal from constantly emitting sources while
147 dampening more sporadic, background emissions from biomass burning, soils, and light-
148 ning.

149 Once the point sources were identified, we calculated daily TROPOMI-derived NO₂
150 emissions for the study area using the divergence method (Beirle et al., 2019; Dix et al.,
151 2022) with some modifications described below. This method derives emission based on
152 a divergence term and a sink term, which account for wind dispersion effects and NO₂
153 depletion by OH, respectively. A detailed description of the derivation can be found in
154 Dix et al. (2022). To calculate daily emissions we regridded daily VCD values to a com-
155 mon 0.025° x 0.025° grid. We filtered TROPOMI measurements to avoid clouds, errors,
156 and problematic retrievals by using only those with quality assurance value ≥ 0.75 (H. Es-
157 kes et al., 2022); retrievals with solar zenith angle $> 60^\circ$ were rejected. Hourly values
158 of fields (longitudinal and latitudinal horizontal wind at 100 m from the ground, pres-
159 sure, and temperature) required for the emissions calculation were obtained from ERA5
160 reanalysis. All ERA5 fields were resampled to 0.025° x 0.025° spatial resolution and in-
161 terpolated to the passing time of the closest (spatially and temporally) TROPOMI ob-
162 servation. Fields provided on pressure levels were interpolated to an altitude of 100 m
163 above the ground. In our implementation, OH lifetime was calculated for each data point
164 based on the solar zenith angle of the closest TROPOMI retrieval. Daily emissions were
165 averaged into annual means.

166 To calculate the actual NO₂ emissions released from each point source, background
167 NO₂ emissions must be quantified and removed from the raw (non-background corrected)
168 emissions. Several background removal approaches are possible: Beirle et al. (2019) sub-
169 tracted from the emissions their 10th percentile value, Dix et al. (2022) removed the mode
170 of a Gaussian curve fit to them. We find that the former is better suited to study regions
171 with homogeneous background emissions and that results from the latter are highly de-
172 pendent on how the Gaussian curve is defined. Similarly, statistics derived from two-dimensional

173 Gaussians fitted to the point source emissions (Beirle et al., 2019) were, in our case, highly
174 dependent on location and size of the area selected to perform the fit. Our approach con-
175 sisted of calculating annual statistics (mean and standard deviation) for each point source
176 plume as well as for its local background area: a $\sim 1^\circ \times 1^\circ$ region surrounding each point
177 source, excluding the point source plume. The location and extent of the point source
178 plumes were identified based on an empirical threshold ($0.37 \text{ kg km}^{-2} \text{ h}^{-1}$) applied to
179 mean raw emissions from the 2019-2022 period. Annual means of background-removed
180 emissions were calculated for each point source by subtracting its mean background value
181 from its mean raw emission value.

182 Dix et al. (2022) described in detail the effects of individual parameters (e.g., back-
183 ground correction, wind level, wind data source, OH lifetime, VCD thickness) on the re-
184 sults obtained using this method. We investigated ERA5 wind data uncertainty effects
185 by using the spread of its wind field 10 member ensemble to perturb 2020 NO_2 emissions.
186 The spread provides an estimate of relative, random uncertainty; ensemble, mean, and
187 spread are part of the ERA5 dataset. The results show that ERA5 wind uncertainty pro-
188 duces small changes in raw NO_2 emission ($< 4\%$; Table S1 and Fig. S1).

189 4 Results

190 Six distinct point sources are clearly visible in the mean 2019-2022 TROPOMI NO_2
191 VCD map (Fig. 1; Fig. S2 shows annual mean VCD maps). Four of the point sources
192 correspond to large copper (Sentinel, a.k.a. Trident; Lubumbashi; Kansanshi) or copper-
193 cobalt (Kolwezi and adjacent Katanga) open-pit mines. The remaining two point sources
194 coincide with cities (Lubumbashi and Ndola) where we infer that high-emission indus-
195 trial activities take place, as explained below. Latitudinal profiles of mean annual VCD
196 across each point source (Fig. 1) show that background NO_2 remains nearly constant
197 year to year while the point sources (well defined, narrow peaks of fixed location) vary
198 in magnitude. TROPOMI emission results (Table 1 and Fig. S3) reinforce these obser-
199 vations. TROPOMI NO_2 mostly increased with time at all the point sources but one,
200 Ndola, where background-removed emissions decreased by $> 70\%$ between 2019 and 2022.

201 To understand these inter-annual trends in NO_2 emissions, we compared background-
202 removed TROPOMI-derived emissions to mine production data where available (Table
203 1 and Fig. 2). Most of the energy consumed in copper or copper-cobalt mining, includ-
204 ing electricity, is generated by diesel fuel combustion. Mining equipment consumes ~ 60
205 % of the total energy; comminution $\sim 36\%$; flotation, filtering, and drying $\sim 4\%$ (Allen,
206 2021). Limited data relevant to energy consumption is provided in mining company re-
207 ports; we found the best proxy for energy (i.e., diesel) consumed to be amount of ore and
208 waste mined. Panels b, c, and d in Fig. 2 show strong positive correlation between an-
209 nual values of total ore plus waste mined versus NO_2 emissions for the Sentinel, Lumwana,
210 and Kansanshi mines ($R = 0.84, 0.74,$ and 0.79 , respectively). Amount of copper pro-
211 duced (highly dependent on ore grade, among other factors, and thus, a less-desirable
212 proxy) was used for the Kolwezi-Katanga mines (Fig. 2.a) for lack of ore and waste data
213 ($R = 0.84$).

214 The remaining two point sources coincide with some of the largest cities in the study
215 area: Lubumbashi (DRC, population $> 2.6 \times 10^6$) and Ndola (Zambia, population > 0.5
216 $\times 10^6$). To discard the hypothesis that their emissions are due to urban activity alone,
217 we quantified NO_2 emissions for two additional cities of similar size: Mbuji-Mayi (DRC,
218 population $> 2.7 \times 10^6$), located 750 km northwest of Lubumbashi; and Kitwe (Zambia,
219 population $> 0.7 \times 10^6$), 50 km northwest of Ndola (labeled g in Fig. 1 map). (Popu-
220 lation data are for 2022 urban areas (Population Stat, 2023).) The results (Fig. 1, Ta-
221 ble S2, and Fig. S4) show that neither the magnitude of VCD or emissions, the spatial
222 extent of the plumes, or the temporal emission trends from Lubumbashi and Ndola can
223 be explained by urban activity alone. Background-removed NO_2 emissions from Lubum-

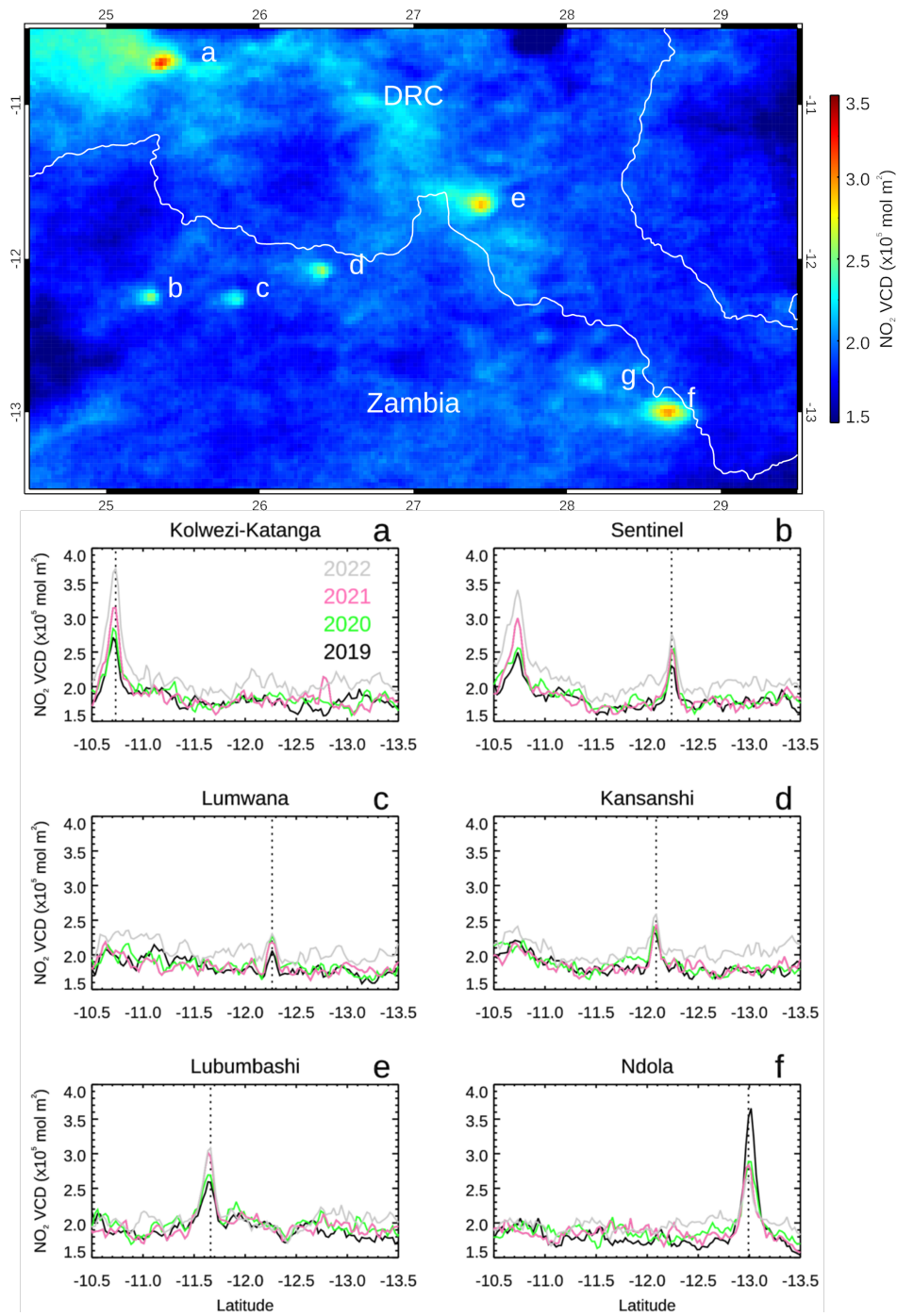


Figure 1. (Top) 2019-2022 mean of TROPOMI NO₂ VCD for the Copperbelt study region. Labels a through f show the six point sources analyzed. Label g shows the location of Kitwe City. White lines indicate country borders. (Bottom) Annual means of TROPOMI NO₂ VCD along latitudinal profiles centered at each of the six point sources, shown by vertical dotted lines. Labels as above. Profiles are color-coded according to year.

Table 1. Production and NO₂ emissions (TROPOMI background-removed, TROPOMI background, inventory) for six Copperbelt point sources. Ore, waste, and copper produced are in ktonnes; copper grade in percentage. Kansanshi reports provide separate copper grade values for sulfide, mixed, and oxide ores. Throughput (slag processed in Lubumbashi, crude refined in Ndola) are in ktonnes. All emissions and their standard deviation values (in parenthesis) are in kg km² h⁻¹.

		2019	2020	2021	2022
Kolwezi ^a , Katanga ^b	Ore, Waste	- , -	- , -	- , -	- , -
	Grade	4.2, -	4.17, -	2.9, -	- , -
	Copper	84.3, 234.5	114.3, 270.7	121.1, 264.4	- , 220.1
	TROPOMI	0.19 (0.10)	0.24 (0.12)	0.31 (0.15)	0.41 (0.17)
	Background Inventory	0.23 (0.08)	0.23 (0.10)	0.22 (0.10)	0.26 (0.10)
Sentinel ^c	Ore, Waste	50263, 92826	60098, 97970	57380, 102445	56219, 95335
	Grade	0.5	0.49	0.47	0.46
	Copper	220.006	251.216	232.688	242.451
	TROPOMI	0.23 (0.11)	0.27 (0.12)	0.33 (0.10)	0.26 (0.11)
	Background Inventory	0.20 (0.07)	0.22 (0.08)	0.21 (0.07)	0.24 (0.07)
Lumwana ^d	Ore, Waste	23230, 62837	26880, 73480	33510, 65499	20277, 78063
	Grade	0.47	0.52	0.46	0.52
	Copper	107.955	125.191	109.769	121.109
	TROPOMI	0.20 (0.06)	0.29 (0.08)	0.27 (0.09)	0.21 (0.06)
	Background Inventory	0.21 (0.07)	0.22 (0.07)	0.21 (0.07)	0.24 (0.07)
Kansanshi ^c	Ore, Waste	36325, 52768	34423, 61972	35142, 69758	28205, 75878
	Grade	0.89, 1.05, 1.12	0.83, 1.00, 0.93	0.88, 0.96, 0.72	0.71, 0.63, 0.57
	Copper	232.243	221.487	202.159	146.282
	TROPOMI	0.22 (0.07)	0.31 (0.09)	0.33 (0.11)	0.28 (0.10)
	Background Inventory	0.22 (0.07)	0.23 (0.08)	0.22 (0.07)	0.24 (0.07)
Lubumbashi ^e	Throughput	-	-	255.229	-
	TROPOMI	0.23 (0.10)	0.23 (0.10)	0.30 (0.16)	0.28 (0.17)
	Background Inventory	0.25 (0.08)	0.26 (0.08)	0.25 (0.08)	0.26 (0.08)
Ndola ^f	Throughput	700.277	372.384	56.672	0 ^g
	TROPOMI	0.58 (0.30)	0.32 (0.10)	0.26 (0.13)	0.17 (0.10)
	Background	0.20 (0.09)	0.21 (0.09)	0.21 (0.08)	0.23 (0.08)
	Inventory	0.22	0.22	0.22	-

^aZijin (2023). ^bGlencore (2023). ^cFirst Quantum (2023a). ^dBarrick (2023). ^eSTL (2023). ^fMwila et al. (2022). ^gInactive.

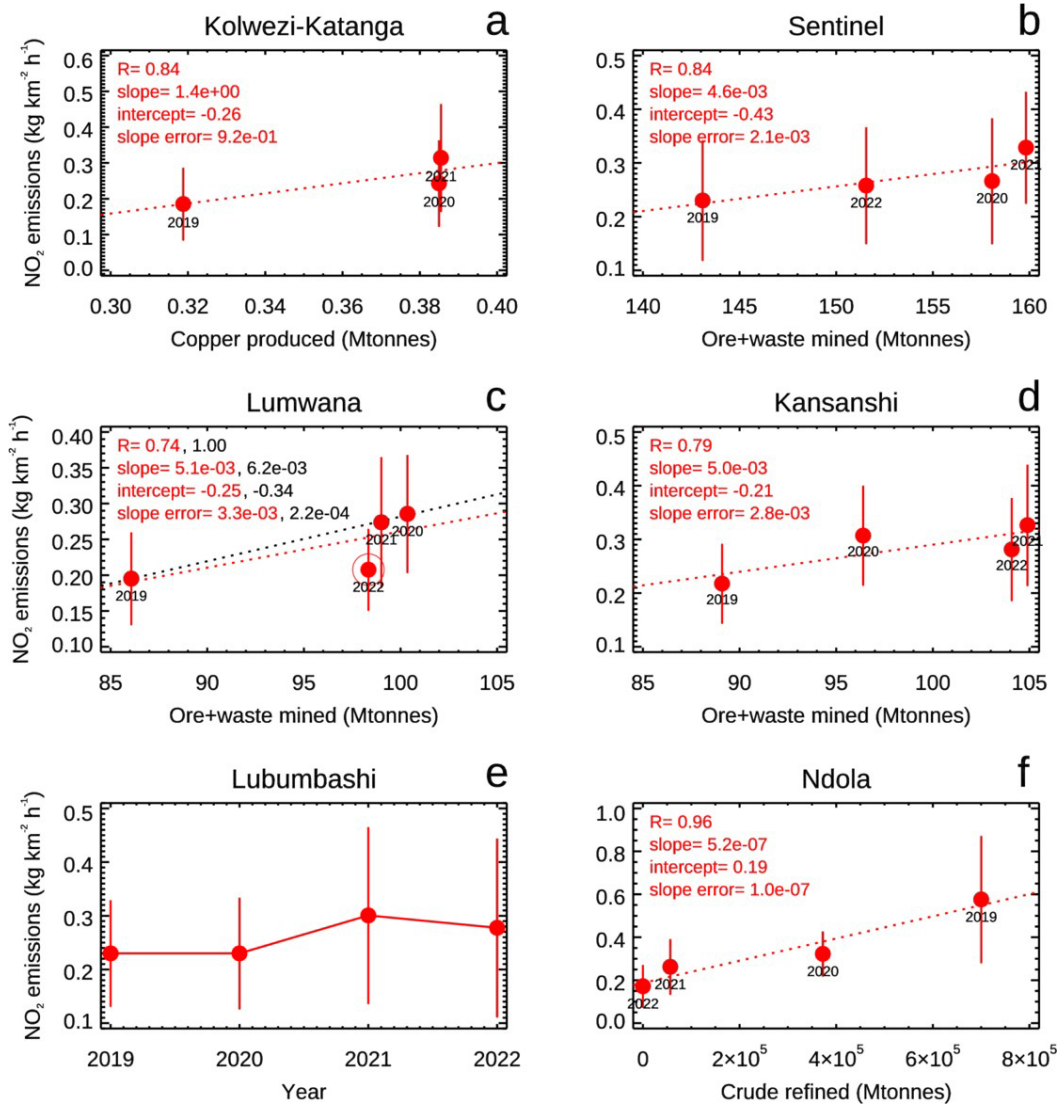


Figure 2. TROPOMI-derived, background-removed NO₂ emissions and their standard deviation versus production, except (e), where production data is unavailable. (c) Statistical values and fit line in black exclude 2022 values; see text for details.

224 bashi are higher than those from Mbuji-Mayi by 90 %, even though the population of
 225 the former is lower by 2 %. Similarly, while its population is lower by 27 %, emissions
 226 from Ndola surpass those from Kitwe by 40-80 %, depending on the year, and display
 227 inter-annual variations which do not correlate with changes in population. These find-
 228 ings are consistent with our hypothesis that emissions from Lubumbashi and Ndola are
 229 not the result of urban activity alone. We researched other possible origins for the ex-
 230 cess emissions observed at these two point sources. We hypothesize that Lubumbashi's
 231 high NO₂ emissions are due to reprocessing of the Lubumbashi slag heap: a 14.5 × 10⁶
 232 tonne hill of mining residue located inside the city, resulting from metallurgical activ-
 233 ity between 1924 and 1992 (Peřsa, 2022). Copper, cobalt, and zinc are extracted from the
 234 slag heap by La Société Congolaise du Terril de Lubumbashi (2000-present). Reports from
 235 the local press attest to the pollution resulting from the operation (Africa Intelligence,
 236 2021). Figure 2.e shows annual background-removed TROPOMI-derived NO₂ emissions;
 237 because production data is incomplete (STL, 2023; The Carter Center, 2023), emissions
 238 and mining-related activity cannot be compared in this case. The most plausible emis-
 239 sions source in Ndola is the INDENI petroleum refinery plant, located inside the city.
 240 Inactive since late 2021, its declining production values (Mwila et al., 2022) match well
 241 the TROPOMI-derived NO₂ emissions (R = 0.96, Fig. 2.f).

242 The six Copperbelt NO₂ emission point sources do not coincide with SO₂ enhance-
 243 ments, as shown by the map of mean TROPOMI SO₂ VCD values for the period between
 244 January 2019 and July 2022 (Fig. 3). The map shows SO₂ enhancements elsewhere: col-
 245 located with the Hwange coal power plant (Zimbabwe), the Selous smelter (Zimbabwe), and
 246 the Chingola and Mufulira smelters (Zambia).

247 Anthropogenic emissions from the inventory were compared to TROPOMI-derived
 248 emissions from our six point sources. Monthly inventory emissions from the following
 249 sectors were aggregated: power generation, industrial processes (including mining), road
 250 and non-road transportation, residential, fugitive fuel emissions, solvents application and
 251 production, and solid waste and wastewater handling. Emissions from the agriculture
 252 livestock, agriculture soils, and agriculture waste burning sectors would be part of the
 253 background over mines and cities and, thus, were excluded. Aggregated inventory emis-
 254 sions were converted to NO₂ ($NO_2 = NO_x / 1.32$; Beirle et al. (2019), Dix et al. (2022)).
 255 The highest inventory value among the nine data points coinciding spatially with each
 256 point source was selected; annual inventory means were calculated and compared to their
 257 background-removed TROPOMI-derived emissions counterparts (Table 1 and Fig. S5).
 258 The inventory underpredicts mine emissions by 61-96 %, generally overpredicts city emis-
 259 sions, and does not identify the annual trends in both TROPOMI-derived emissions and
 260 mine production.

261 5 Discussion

262 We have shown that NO₂ from copper/cobalt mining and other industrial activ-
 263 ities can be identified and emissions quantified from satellite, even in the presence of high
 264 background values from biomass burning, soils, and lightening. Furthermore, we have
 265 demonstrated strong positive correlations between annual TROPOMI-derived NO₂ emis-
 266 sions and mine production/refinery throughput. These correlations are mine-dependent
 267 and cannot be extrapolated from mine to mine; differences in ore grades and equipment
 268 fuel efficiency are probably the main causes. As an example, lower-than-expected 2022
 269 emissions from Lumwana, which reduced R from 1.00 (for 2019-2021) to 0.74 (for 2019-
 270 2022) (Fig. 2.c), can be traced to a new fleet of trucks and shovels commissioned in 2021
 271 (Barrick, 2023) and in operation during 2022 (Lusaka Times, 2022).

272 As a reference, 2019 background-removed TROPOMI-derived NO₂ emissions from
 273 Ndola (0.044kg/s , after accounting for point source area) are equivalent to NO₂ emis-
 274 sions from the Miami Fort or the Intermountain coal power plants, both among the ten

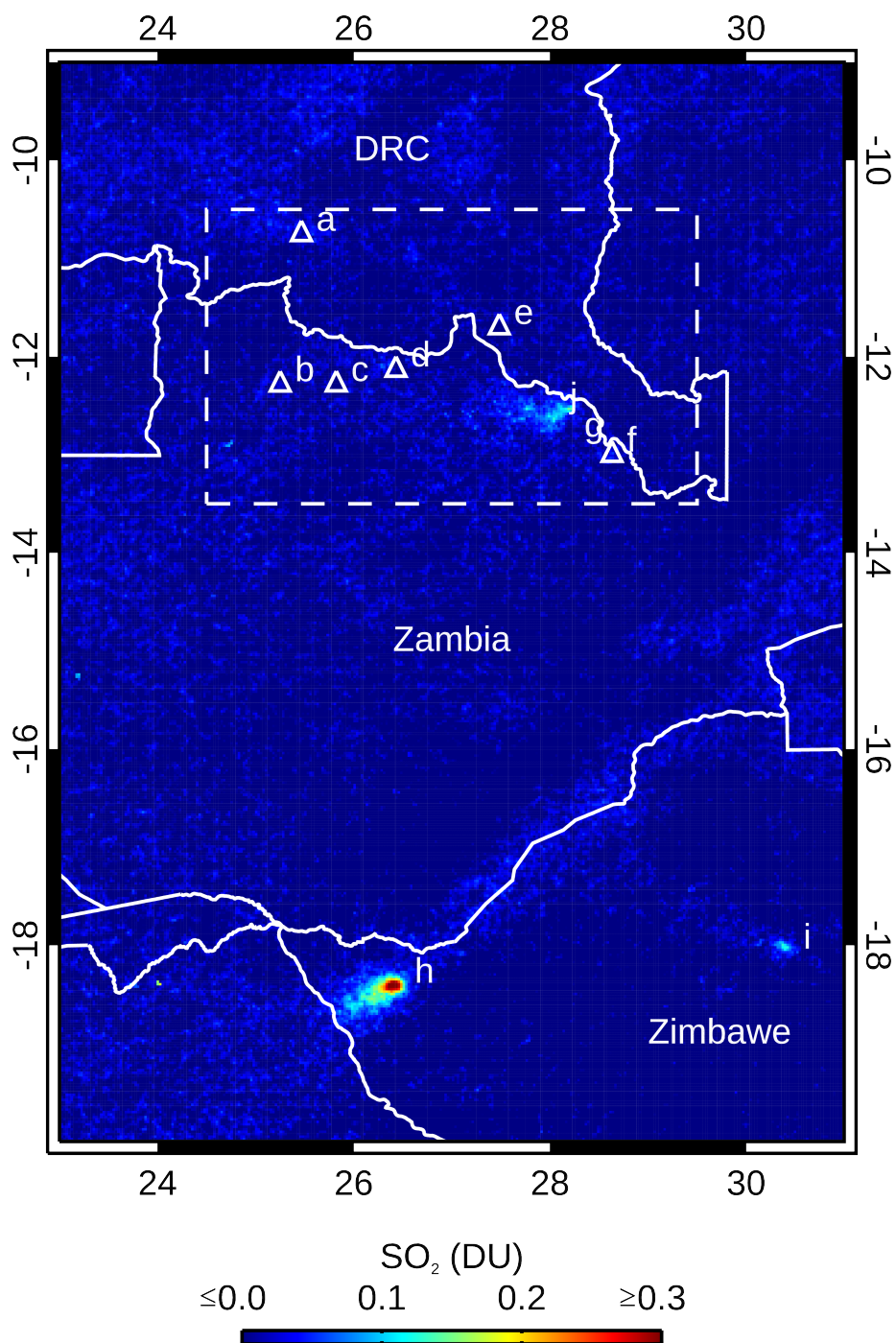


Figure 3. Mean TROPOMI-COBRA SO_2 VCD for January 2019 - July 2022. White triangles show the Copperbelt NO_2 emission point sources analyzed. (a) Kolwezi-Katanga. (b) Sentinel. (c) Lumwana. (d) Kansanshi. (e) Lubumbashi. (f) Ndola. (g) Kitwe. (h) Hwange coal power plant. (i) Selous smelter. (j) Chingola-Mufulira smelters. White lines show country boundaries. Dashed white lines show Copperbelt study area.

275 largest NO_x emitters in the USA that year (Beirle et al., 2021). Our results demonstrate
276 that the impact of mining/oil refining on local air quality can be quantified using satel-
277 lite data; this is particularly important for African regions where mining and other in-
278 dustrial activities proliferate without sufficient air quality monitoring.

279 We have analyzed the point sources with the highest mean annual TROPOMI-derived
280 emissions in the Copperbelt; our maps do, however, show a string of NO₂ enhancements
281 along the Ndola-Lubumbashi-Kolwezi corridor (Fig. 1) where relatively smaller copper/cobalt
282 mining operations, both industrial and artisanal, exist. Future work should explore the
283 detection limits of this method by analyzing some of these other NO₂ enhancements.

284 Ground emission measurements were unavailable; thus, we compared background-
285 removed TROPOMI-derived NO₂ emissions to inventory data. Inventory values are lower
286 (higher) for mines (cities) than their TROPOMI counterparts and do not capture the
287 annual trends revealed by TROPOMI. The remoteness of the region, lack of field data,
288 and relatively small size of the point sources may explain at least in part these discrep-
289 ancies. NO₂ emissions derived from satellite measurements could improve the overall mag-
290 nitude and temporal (seasonal, inter-annual) trends in inventory emissions. They could
291 also be used to refine regional emission factors, which are not well defined for Africa.

292 We identified SO₂ enhancements coinciding with smelters and a coal power plant
293 elsewhere, but none collocated with our NO₂ point sources (Fig. 3), despite the fact that
294 some of them either include a smelter (Kansanshi, First Quantum (2023a)) or have one
295 nearby (Lualaba, 40 km southeast of Kolwezi; Ivanhoe Mines (2021)). Lack of SO₂ en-
296 hancements indicates use of technologies to convert sulfur oxides released from the ore
297 during smelting into sulfuric acid, a commercial byproduct (Hocking, 2005; Ialongo et
298 al., 2018). The use of such technologies in the Kansanshi and Lualaba smelters has been
299 documented by the mining companies involved (Gray et al., 2020; First Quantum, 2023b;
300 Wang, 2020).

301 **6 Conclusions**

302 Understanding the environmental effects of high-impact minerals extraction and
303 processing is of great relevance (Hund et al., 2020), particularly if the mining-related ac-
304 tivities take place in close proximity to -or even inside of- population centers, as is the
305 case in the Copperbelt region. We have shown for the first time that NO₂ emissions from
306 copper and cobalt mining activities can be identified and measured using TROPOMI satel-
307 lite data, even in the presence of high background NO₂; this is important in the absence
308 of local air quality monitoring. Furthermore, we have shown, also for the first time, a
309 strong positive correlation between TROPOMI-derived NO₂ emissions and mining/oil
310 refining production data. We note that these correlations are mine-dependent and that
311 changes in the mine's environment (ore grade, fuel efficiency) will affect such correlations,
312 as observed in Lumwana. The lack of SO₂ enhancements collocated with our NO₂ point
313 sources (enhancements identified, though, in power plants and smelters nearby) is con-
314 sistent with SO₂ capture and transformation into sulfuric acid, which is then used in mining-
315 related processes or commercialized.

316 Because the NO₂ emissions analyzed result from the combustion of fossil fuels by
317 machinery (e.g., trucks, crushers, generators) used extensively in mining operations, these
318 results are relevant to mining in general, regardless of the resource mined. They are also
319 relevant to oil refineries, as shown in Ndola. We hypothesize that our findings apply to
320 fossil-fuel intensive industries in general.

321 Our results show that NO₂ trend analysis can be used to predict mine production
322 and refinery throughput before companies release their reports or in lieu of these reports
323 in case of non-publicly traded companies, which are not required to publish their activ-
324 ity data. Insufficient emissions from mines claiming high production may be indicative

325 of production from a different source. Thus, this method may be useful for improving
 326 traceability of minerals extracted in conflict areas and smuggled into the global supply
 327 chain despite existing traceability and tagging schemes, an issue highlighted in the most
 328 recent releases of the United Nations Yearbook (United Nations, 2019, 2022).

329 **Open Research Section**

330 Atmospheric data available as follows. TROPOMI NO₂ data (L2_NO2_) are publicly available via
 the ESA's S5P Pre-Ops interface (<https://scihub.copernicus.eu/>) using the credentials given there.
 TROPOMI SO₂ COBRA data:

<https://distributions.aeronomie.be/?menu=68c9f961bc294141c215e3d64a6ae282#>. ERA5 data:
<https://cds.climate.copernicus.eu/cdsapphttps://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form> (hourly data on single levels) and

<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form> (hourly data on pressure levels). CAMS-GLOB-ANT inventory data are publicly
 available via the <https://eccad3.sedoo.fr/> interface following the instructions given there to create a free
 access account. Mining production data available from mining company reports as follows. First
 Quantum Minerals Ltd. (Sentinel, Kansanshi):

https://s24.q4cdn.com/821689673/files/doc_downloads/2019-annual-report/First_Quantum_AR_2019.pdf (2019),

https://s24.q4cdn.com/821689673/files/doc_downloads/2020-annual-report/First_Quantum_2020_Annual_Report.pdf (2020), https://www.firstquantum-2021-annual-report.com/files/ugd/acdda3_c51ed134aa184e259d61a629344f98e7.pdf (2021), https://www.first-quantum.com/files/doc_downloads/2022-annual-report/First-Quantum-2022-AR-online.pdf (2022).

Barrick Gold Corporation (Lumwana):

https://s25.q4cdn.com/322814910/files/doc_financial/annual_reports/2019/Barrick-Annual-Report-2019.pdf (2019), https://s25.q4cdn.com/322814910/files/doc_financial/annual_reports/2020/Barrick-Annual-Report-2020.pdf (2020),

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<https://www.zijinmining.com/upload/file/2020/09/14/9c97a89f8e9c4c59a13f2404f3bb1096.pdf> (2019),
<https://www.zijinmining.com/upload/file/2021/06/09/538a46cc4831452e97b30cae55c9cf97.pdf> (2020),

<https://www.zijinmining.com/upload/file/2022/06/20/771c971d76154257882f58ed03643c07.pdf> (2021);

no 2022 annual report available at the time of writing). Glencore (Katanga):

<https://www.glencore.com/.rest/api/v1/documents/5a08fe1942f92df7f2301ac3681e23aa/glen-2019-annual-report-interactive.pdf?download=true> (2019),

https://www.glencore.com/.rest/api/v1/documents/3505497f3cb94b24f0c79f5ba32b293b/Glencore_AR20_Interactive+%281%29.pdf?download=true (2020),

<https://www.glencore.com/.rest/api/v1/documents/ce4fec31fc81d6049d076b15db35d45d/GLEN->

[2021-annual-report-.pdf?download=true](#) (2021),
<https://www.glencore.com/.rest/api/v1/documents/ded10fa92974aa388a43aa9f86f483e9/GLEN-2022-Annual-Report.pdf> (2022).

ERA5 data are produced by C3S and CAMS. Contains modified information from C3S and CAMS [2019-2021]. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information data contained in this study.

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