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The impact of COVID-19 lockdown on surface air quality changes in major African countries

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Abstract.

The lockdown during the coronavirus disease 2019 (COVID-19) pandemic provides a natural experience to examine the air quality changes from emission reductions. However, limited monitoring data has made it challenging to study these changes in major African regions. This study aimed to assess air quality changes, including major pollutants such as CO, NO_2, O_3, SO_2, and aerosol particles during COVID-19 lockdowns in 2020 across different African countries. Using chemical reanalysis products from the Jet Propulsion Laboratory, we calculated quarterly dual anomalies and quarterly anomalies for MAM (March to May) and JJA (June to August) in 2020. Results showed a general decline in CO, NO_2, O_3, and nitrate aerosol across majority African countries, with more pronounced decreases during JJA. However, discrepancies were also seen: quarterly dual anomalies revealed a decrease in NO_2 and SO_2 in Northern Africa (NA), while quarterly anomalies showed an increase, suggesting containment policies moderated the increase rates. In Southern Africa (SA), both methods observed increases in SO_2, likely due to relaxed restrictions and heightened energy demands. Sensitivity diagnostics showed that the increase in O_3 in South Africa may be related to the decrease in NO_2. Additionally, increased in sulfate and ammonium aerosols in NA and SA was likely attributed to dust events and higher residential emissions, respectively. For this study, we concluded that air quality changes may be intertwined with both natural and anthropogenic influences and the results highlight the necessity for stricter emission standards for coal-fired plants and promote clean energy in African countries.

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1 Introduction

The strict containment policies during the outbreak of coronavirus disease 2019 (referred to as COVID-19) in 2020, such as partial or complete closure of international borders, schools, and non-essential businesses, as well as restrictions on citizen movement in some cases (Pepe et al., 2020), provided a natural experiment to investigate how the air quality will respond to potential strict control policies (Navinya et al., 2020; Sikarwar and Rani, 2020; Singh and Chauhan, 2020). Numerous studies have investigated the air quality changes due to the lockdown measures across different worldwide regions using surface observation, air quality modelling and satellite retrievals. However, the responses of the air quality changes were highly depending on the species and location, and were not always consistent.

Many studies have shown that strict lockdown measures have led to significant improvements for certain pollutants, but no noticeable decrease for the other. Take a few as example, the cities of Chongqing, Luzhou, and Chengdu in China experienced the largest decreases in NO_2 and sulfur dioxide (SO_2) by 62.1% and 83.8% individually during February 2020 when compared with the same month in previous years (2017–2019), while carbon monoxide (CO), PM_{10}, and $PM_{2.5}$ had relatively smaller decreases, ranging from 17.9% to 30.8%. Surprisingly, O_3 concentration increased by 6.2% instead (Zhang et al., 2020). In addition, although reduced anthropogenic emissions during the lockdown period led to an obvious decrease in $PM_{2.5}$ across most provinces in China, unfavourable weather conditions, mainly less rainfall, lower planetary boundary layer (PBL) and wind speed, higher relative humidity (RH) and temperature, resulted in only half of its precursor's decline (Wang et al., 2020). During the recent lockdown period in Shanghai, China from April to May 2022, both surface and column NO_2 were observed a significantly decreases. However, surface formaldehyde (HCHO) was found to increase by 13%, and O_3 had no significant changes due to the weakened titration effects from reduction in NO (Tan and Wang, 2022). As one of the cities severely affected by the COVID-19 pandemic after Wuhan, Milan in Italy also observed a significant decrease in NO_2 during the lockdown period. However, while there was a 20% reduction in SO_2 concentration in urban areas, there was no change in SO_2 levels in suburban areas, possibly due to more closures of public places in urban areas resulting in a decrease in heating demand, but the suburban heating demand has not dropped significantly. Meanwhile, O_3 concentrations significantly increased in urban areas, which could be attributed to chemical oxidation reactions caused by increased sunlight hours and decreased NO_2 concentrations (Collivignarelli et al., 2020). During the lockdown period, NO_2 concentrations were also found to decrease significantly in the United States (Goldberg et al., 2020; Muhammad et al., 2020; Qu et al., 2021), while $PM_{2.5}$ only decreased in metropolitan areas of Northeastern and California/Nevada regions with O_3 concentrations remaining relatively stable (Chen et al., 2020c). Similar phenomena has also been found in other countries such as India (Navinya et al., 2020; Mor et al., 2021), Bangladesh (Kganyago and Shikwambana, 2021), Brazil (Siciliano et al., 2020), Spain (Baldasano et al., 2020), and EU member states (Varga et al., 2024). Meanwhile a few studies also investigated the impact of lockdown measures on air quality changes from a global perspective (Venter et al., 2020; Miyazaki et al., 2021; Sekiya et al., 2023), with assimilated high-resolution OMI and TROPOMI satellite retrievals or ground observation data. It was found that although global anthropogenic

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NO_2 emissions decreased significantly during the lockdown periods in 2020, the decreases in $PM_{2.5}$ were smaller than that of NO_2 or even remained unchanged (Venter et al., 2020; Chossière et al., 2021; Shi et al., 2021). Additionally, due to the high local ozone production efficiency in Asia and America, there were little changes in the global tropospheric ozone burden (Miyazaki et al., 2021). Furthermore, Shi et al. (2021) discovered that the decreases in NO_2 concentrations in 11 typical cities were lower than expected through deweathering machine learning techniques, indicating the importance of weather conditions on the air quality changes. However, to our best knowledge, few studies have been focused on African continent mainly due to the lack of well-developed ground monitoring sites and the lack of attention and funding for the African environment (Mead et al., 2023).

As the region with the highest exposure to $PM_{2.5}$ in the world, Africa's air pollution problem cannot be overlooked. With the rapid urbanization, economic development, and increasing reliance on fossil fuel combustion (Garcia et al., 2021; Katoto et al., 2019; Navaratnam et al., 2024), the air pollution-induced mortality burden has become the second leading cause of death in Africa (Health Effects Institute, 2022; Fisher et al., 2021). The epidemic lockdown has also provided an "opportunity scenario" to investigate the effectiveness of emission reduction policies to improve air quality in African countries. Some available studies have been carried out to study the air quality changes in specific African cities or regions by utilizing sporadic monitoring station data (Khomsi et al., 2021) and remote sensing (Yusuf et al., 2021). For example, in several cities of Morocco, during the lockdown period, there was a significant decrease in NO_2 compared with before the lockdown, and $PM_{2.5}$ also relatively decreased (Singh et al., 2020b; Khomsi et al., 2020, 2021). In some cities in Nigeria, O_3 concentration increased slightly, while NO_2 concentration decreased in March but slightly increased in April. SO_2 concentration during the lockdown months (March and April) increased compared with previous years but exhibited a lower level than January and February (Fuwape et al., 2020). Using OMI retrieved data, NO_2 emissions decreased by 15% and 33% in Cairo and Alexandria of Egypt respectively, with slight decrease of CO (approximately 5%), and increase of ozone by about 2% compared with the years 2015-2019 (Mostafa et al., 2021). In Kampala, Uganda, one of busiest cities in Eastern Africa, the Air Quality Index (AQI) showed a 6.6% decrease during the lockdown period (March to July) compared with the previous year (Abisha Meji et al., 2020).

The main purpose of this study is to investigate the concentration changes of gas and aerosol pollutants during COVID-19 lockdown periods in major African continents during the boreal spring (March to May, referred as MAM) and boreal summer (June to August, referred as JJA) seasons. We utilize chemical reanalysis products from the state-of-the-art multi-component satellite data assimilation system (Miyazaki et al., 2020a; Miyazaki et al., 2020c; Miyazaki et al., 2021), which optimizes pollutant concentrations and emissions by assimilating multiple satellite observations and considering chemical interactions between different gases. To isolate the effects of temporal emission changes and interannual meteorological variations, we applied two distinct methods in quantifying the air quality changes, including the quarterly mean anomalies (the difference in pollutant concentration between 2020 and reference years (2005-2019)), and difference-to-difference (the difference between

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the February mean anomaly and the quarterly mean anomaly). We also calculated the pearson correlation coefficients between pollutant concentrations changes and stringency index or meteorological condition changes to quantify and compare their strengths of correlation during the MAM and JJA.

2 Data and methodology

2.1 Study area

Figure S1 shows the map of the study area which covers the whole Africa continent including 50 countries which lies between 40°S–40°N and 20°W–40°E, except some islands such as Cabo Verde, São Tomé and Principe, Comoros, Mauritius, Mayotte, Réunion, Seychelles and Saint Helena. We further separated Africa countries into the following regions, including Northern Africa (NA), Central Africa (CA), Western Africa (WA), Eastern Africa (EA), Southern Africa (SA) as adopted by United Union (Fig. S1).

2.2 Government restrictions in Africa

Since March 2020, African countries have implemented different restrictive policies in response to the COVID-19 pandemic. We obtained the indicator of the lockdown stringency measures developed by (Hale et al., 2021) to quantify the containment intensity in African countries. The index, which ranges from 0 to 100 (Fig. S2), tracks the multiple measures and responses to the COVID-19 crisis over time at a daily resolution, including school and workplace closings, public transport closings, international travel restrictions, and so on. From Figure 1 we can see that overall, the stringency index in the African continent is higher in JJA than those in MAM, meaning that the lockdown measures were generally stricter, such as Mozambique, Ethiopia, S. Sudan, Libya, Malawi, Guinea, Uganda and Nigeria. As shown in Figure 1c, the stringency indexes of all CA countries have increased in the JJA compared to the MAM, while other regions in Africa have mixed changes. There were 18 countries where the stringency index in the MAM was higher than those in the JJA, such as Tunisia, Burkina Faso, Niger, Somali, Mauritania, Sierra Leone, Senegal, Benin. In MAM, the countries with the highest stringency index include Morocco (78.4), Libya (78.2), Kenya (74.5), Tunisia (74.5), Uganda (72.9), while in JJA, Libya (92.1), Uganda (86.0), S. Sudan (82.2), Ethiopia (80.6) and Gabon (80.6) had the highest stringency index (Table S1). Interesting to notice that countries with lower stringency index which were below 50, such as Burundi, Niger, Tanzania, Zambia, and Somalia (Table S1), usually released their restriction earlier, meaning those countries usually have a higher stringency index in MAM than that in JJA (Fig. 1c).

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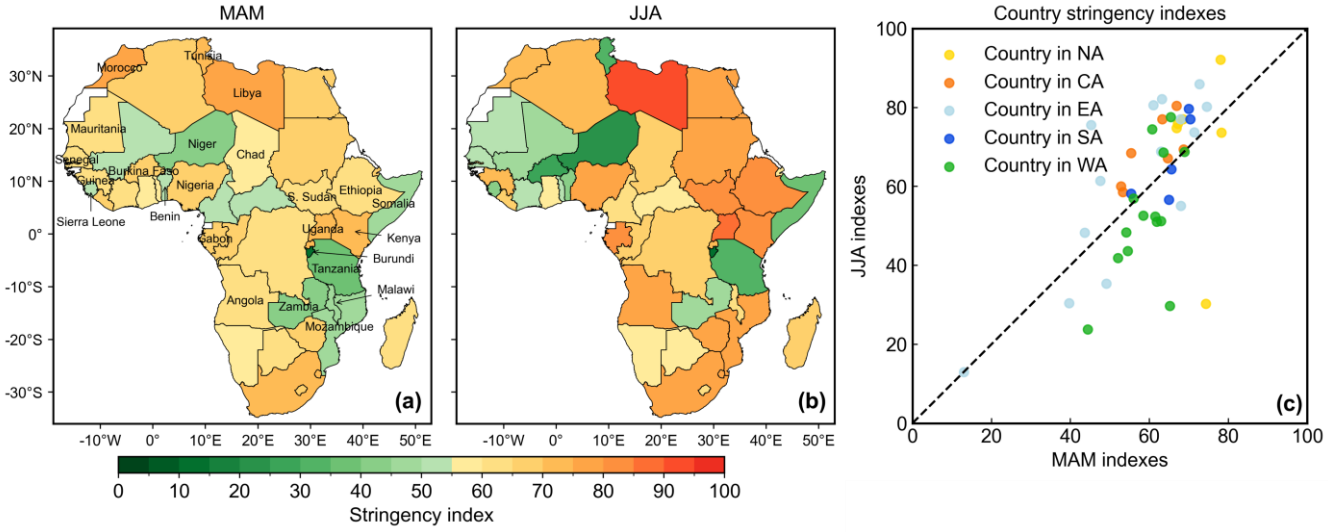

Figure 1: The stringency index weighted average in major African countries in MAM (a) and JJA (b), and the changes from MAM to JJA (c). Among them, the countries in white (Figure a, b) lack containment information.

2.3 Surface air quality data

In this study, we used the long-term chemical reanalysis products constructed by NASA Jet Propulsion Laboratory (https://tes.jpl.nasa.gov/tes/chemical-reanalysis/products/two-hourly, last accessed March 10, 2024). The chemical reanalysis products used a multi-component satellite data assimilation system (Miyazaki et al., 2020c) to assimilate the results of CO, NO_2, SO_2, O_3, and HNO_3 measurements from multiple satellites. Data assimilation uses MICROC-CHASER predictive models to simulate various processes, including transport, emissions, deposition, and chemical reactions such as ozone and aerosol processes. Integrated Kalman filtering technique was employed to combine prior data (predictions) and observational data for obtaining optimal state estimation (Miyazaki et al., 2020b). During the optimization of pollutant emission estimates, only total combined emissions were optimized, while proportions of different emission categories from previous emission estimates were applied at each grid point to obtain assimilated posterior anthropogenic emissions (Miyazaki et al., 2021). Prior surface NO_x and SO_2 emissions in 2020 were derived from the Hemispheric Transport of Air Pollution version 2.2 at a resolution of 0.1° for the anthropogenic emission (Janssens-Maenhout et al., 2015), Global Fire Assimilation System version 1.2 at a resolution of 0.1° for the fire emissions (Kaiser et al., 2012), and Global Emissions Initiative at a resolution of 0.5 degrees for the soil NO_x emission (Janssens-Maenhout et al., 2015; Kaiser et al., 2012; Yienger and Levy Ii, 1995). Lightning NO_x sources in the model were calculated using corresponding parameterizations at each model time step (Price and Rind, 1992). The emissions in 2020 were constrained by various satellite measurements including NO_2, SO_2, CH_4, CO, and ozone (O_3), with the quality of the reanalysis field evaluated using ozone detection as well as aircraft and satellite observations. Based on TROPOMI NO_2 constraints at a resolution of 0.56°, ground-level NO_X emissions in 2020 have been used to assess global tropospheric ozone response to COVID-19 lockdown measures (Miyazaki et al., 2021).

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2.4 Tropospheric column data for HCHO and NO_2

To help explain the ozone changes in major African countries, we also obtained high-resolution monthly offline products of 2020 HCHO and NO_2 vertical column densities (VCD) from the tropospheric emission monitoring internet service (TEMIS; https://www.temis.nl/index.php, last accessed March 20, 2024) (Van Geffen, 2017) for use from the TROPOspheric Monitoring Instrument (TROPOMI). We used bilinear interpolation to standardize the data resolution to 0.1°×0.1°. Subsequently, the African border shapefile was cut to obtain monthly and quarterly mean concentrations of HCHO and NO_2 across the grid of the main continent of Africa. Finally, we calculated the HCHO/NO_2 ratios for MAM and JJA in 2020.

2.5 Statistical analyses to quantify the air quality changes

For this study, we applied two distinct methods to quantify the air quality changes during the lockdown periods. Following previous studies (such as Chen et al. (2020a); Zhang et al. (2022); Li et al. (2023); Ma et al. (2024)), we first applied the quarterly dual anomalies method (also called the difference-to-differences method) by considering seasonal and long-term variations in air pollution. Specifically, for each country and grid cells in African, we calculated the air quality changes during the lockdown period compared with the pre-lockdown period (February) in 2020, and then compared these changes to those observed during the corresponding periods from reference years (2005-2019). We refer to these changes as quarterly dual anomalies. It can be understood as the rate changes at which the concentration of pollutants decreases or rises during the lockdown period compared with those during pre-lockdown.

Another method we referred as the quarterly anomalies, in which we calculated the seasonal concentrations differences between 2020 and the multi-year mean (from 2005 to 2019) for MAM and JJA individually. In addition, we also reported the rate of changes in pollutant concentration for each country, which was calculated by dividing the quarterly anomalies from the multi-year mean. By performing the Mann-Kendall trend analysis of seasonal changes for the major air pollutants from 2005 to 2019 (Fig. S3), we found that the P-values were all greater than 0.05 in Africa, indicating that there was no significant air quality trends caused by either anthropogenic emissions or meteorological conditions in Africa. Thus, we assume the multi-year average from 2005 to 2019 will be representative of the hypothetical air quality in 2020 if no lockdown measures were implemented, and the quarterly anomalies we calculated were mainly attributed to the emission changes caused by the lockdown measures. To test this hypothesis, we also examined the air quality changes by calculating the differences between values in 2020 with 5-year average from 2015 to 2019 for both methods, and we found similar spatial patterns of air quality changes (Figs. S20-S26).

2.6 Random forest model prediction of pollutants

To isolate the influence of local meteorological changes, we have also applied a random forest (RF) model to predict the pollutants concentration in specific regions of Africa. We focus the countries in CA as there has been a significant decrease in CO levels in this region. We used the average daily values of each feature from February to August 2015-2019 as the training

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set. The features included time (the day of the year), latitude and longitude, as well as meteorological variables such as temperature (T2), humidity, v wind, and u wind. The target variable was the CO concentration. All of the data are from the chemical reanalysis products constructed by NASA Jet Propulsion Laboratory (https://tes.jpl.nasa.gov/tes/chemical-reanalysis/products/two-hourly, last accessed March 10, 2024) and the resolution were uniformly adjusted to 0.5°×0.5° using bilinear interpolation. These predictions are based on historical levels of CO, which include information on past anthropogenic emissions. Therefore, the predicted CO concentrations we obtain still retain the influence of emissions from previous years. In order to improve the accuracy, we simulated for February, MAM, and JJA separately. For model validation, we used a time series split rolling cross-verification based on five splits according to Shen et al. (2024), and the Pearson correlation coefficient (PCC) and low root mean square error (RMSE) were used to measure the performance of the model, as shown in Figure S12. After cross-validation, the optimal model was selected to predict the CO concentrations in 2020 under the previous emission scenario. The "n_estimators" of the model was 108 and "max_depth" was 21. Then, by subtracting the actual CO concentrations in 2020 from the predicted values, we can isolate the air quality changes from the meteorological conditions. Finally, calculate the average concentrations of CO for February, MAM, and JJA respectively.

2.7 Pearson correlation analyses

We then performed Pearson correlation analysis to examine the correlations between pollutants and stringency index or meteorological variables (Cahyono et al., 2023). We firstly calculated the average daily concentration anomalies for SO_2, CO, NO_2, temperature and absolute humidity from March 1 to August 31, 2020. The calculations of the average daily concentration anomalies were similar to the quarterly anomalies we described above. Then, the Pearson correlation coefficients of pollutant daily anomaly with temperature daily anomaly, absolute humidity daily anomaly and the stringency index were calculated from March 1 to May 31 and from June 1 to August 31, respectively.

3 Results

3.1 Changes in primary gas pollutants of CO, SO_2, and NO_2

3.1.1 CO changes

Figure 2 shows the spatial distribution of CO changes in MAM and JJA in African countries estimated from the two methods. In general, we found consistent temporal-spatial CO changes from the two methods, with larger CO decreases observed in JJA than those in MAM, sharing the similar spatial patterns with the country stringency index (Fig. 1). The average CO changes was -55 ppbv (-470 to 22 ppb depending on the country) in Africa during the JJA, compared with -0.10 ppb (-62 to 34 ppb) in MAM (Fig. 2c, d). Meanwhile, the two methods are consistent to show that the countries with the largest CO decline are mainly located in CA, such as Angola (Fig. 2b, d). Previous studies have shown that 90% of fires occurred in sub-Saharan regions were caused by human activities (Xiang et al., 2023; Shikwambana, 2019), especially in JJA the fire season in the

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southern hemisphere (Fig. S4). Thus, we conclude that the constrained human activities during the strict lockdown periods in JJA (Fig. 1) reduced the occurrence of wildfires, and thus leading to the more significant CO decline. Further, light-duty vehicle was another major source of CO especially in the Sahara regions such as Egypt in NA (Mostafa et al., 2021), thus the stricter lockdown measures which restrained the vehicles activities contributed to reduce the CO concentration (Ukpebor et al., 2010). Besides the similar results we draw from the two methods, there are also slightly variations as well, with the quarterly dual anomalies method (Fig. 2a, b) usually showing larger CO decreases in both seasons. Also, we observed a hotspot for CO decreases in Cameroon and Central African Rep. in both seasons using the quarterly dual anomalies (Fig. 2a, b) which were missed by the quarterly anomalies method (Fig. 2c, d). We also found obvious CO increases in MAM especially in NA regions as estimated from the quarterly anomalies method (Fig. 2c), which could be caused by the high natural biomass burning activity in the northern hemisphere Africa (Hua et al., 2024) and less dense population (Fig. S29). To further investigate the contribution of emission changes on the concentration anomalies in 2020, we compared the CO concentration differences in MAM and JJA of 2020 between those estimated in the chemical reanalysis data with the RF-predicted CO concentration which isolated the influence of meteorological changes, and we found similar magnitude changes between these two, confirming our conclusions above (Fig. S11).

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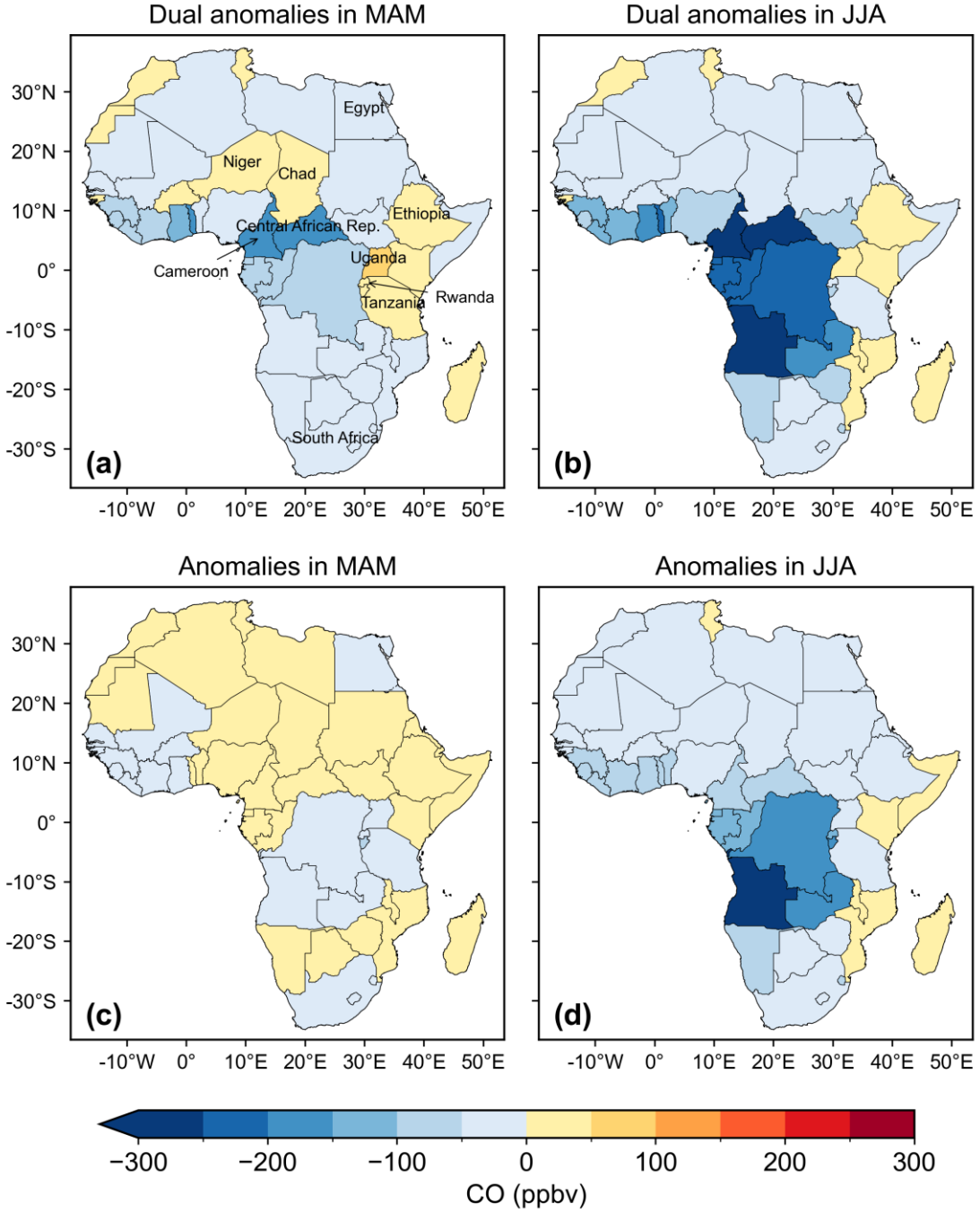

Figure 2: Spatial distribution of CO changes from the two methods: quarterly dual anomalies (a, b), and quarterly anomalies (c, d) for MAM (a, c), JJA (b, d) in African countries. The units are ppbv.

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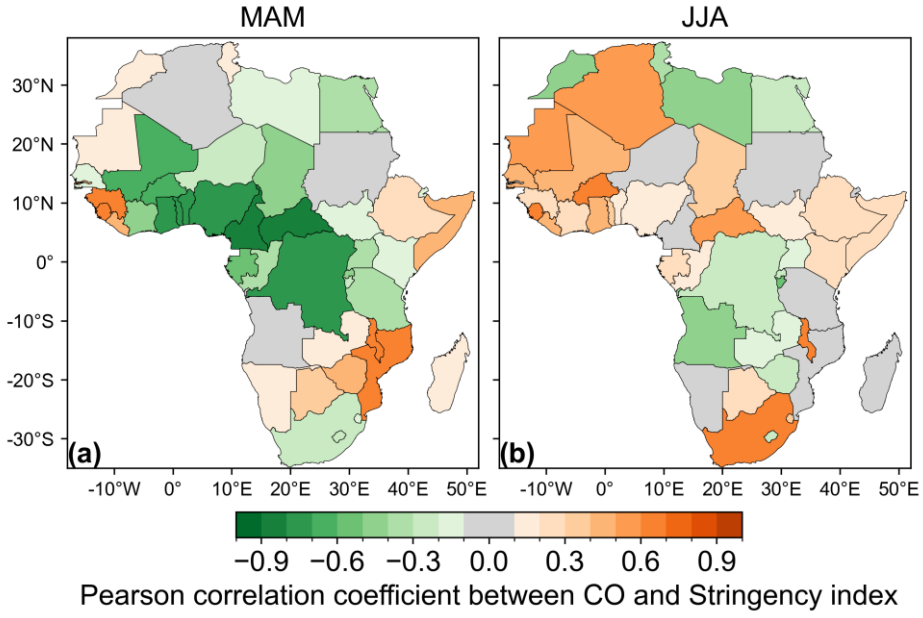

Figure 3: Spatial distribution of pearson correlation coefficients from March 1st to May 31st (a), and June 1st to August 31st (b) in African countries. Positive values denote positive correlations and negative values denotes negative correlations between daily CO anomalies and stringency index.

By calculating the Pearson correlation coefficient between CO anomalies and stringency index (Fig. 3), we found that during the MAM, many countries exhibited a significant negative correlation (Minimum is -0.86) between these two variables. This negative correlation was mainly concentrated in CA, WA and NA, such as Central African Republic, Cameroon, Nigeria, Egypt and South Africa. Although the Central African Republic had moderate lockdown stringency indexes and population levels, its CO concentration still significantly decreased due to its originally higher CO concentration, leading to more noticeable emission reductions. In contrast, despite lower original CO concentrations in Egypt and South Africa, their higher stringency indexes resulted in a decrease in CO concentrations. However, countries like Chad, Niger, Uganda, Rwanda, and Ethiopia still had positive dual anomalies, which may be related to lower stringency indexes in these countries or their neighbours, as well as lower CO concentrations (Fig. S4). During the JJA, the decrease in CO concentrations was negatively correlated with stringency indexes in only some countries, particularly in CA and NA. Because some countries have a lower level of stringency index during the JJA, the Pearson correlation analysis may be affected by unusual occasional changes in pollutants. In conclusion, changes in CO concentration are co-controlled by each country's individual CO emission levels, the lockdown stringency indexes and even population conditions.

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3.1.2 NO_2 change

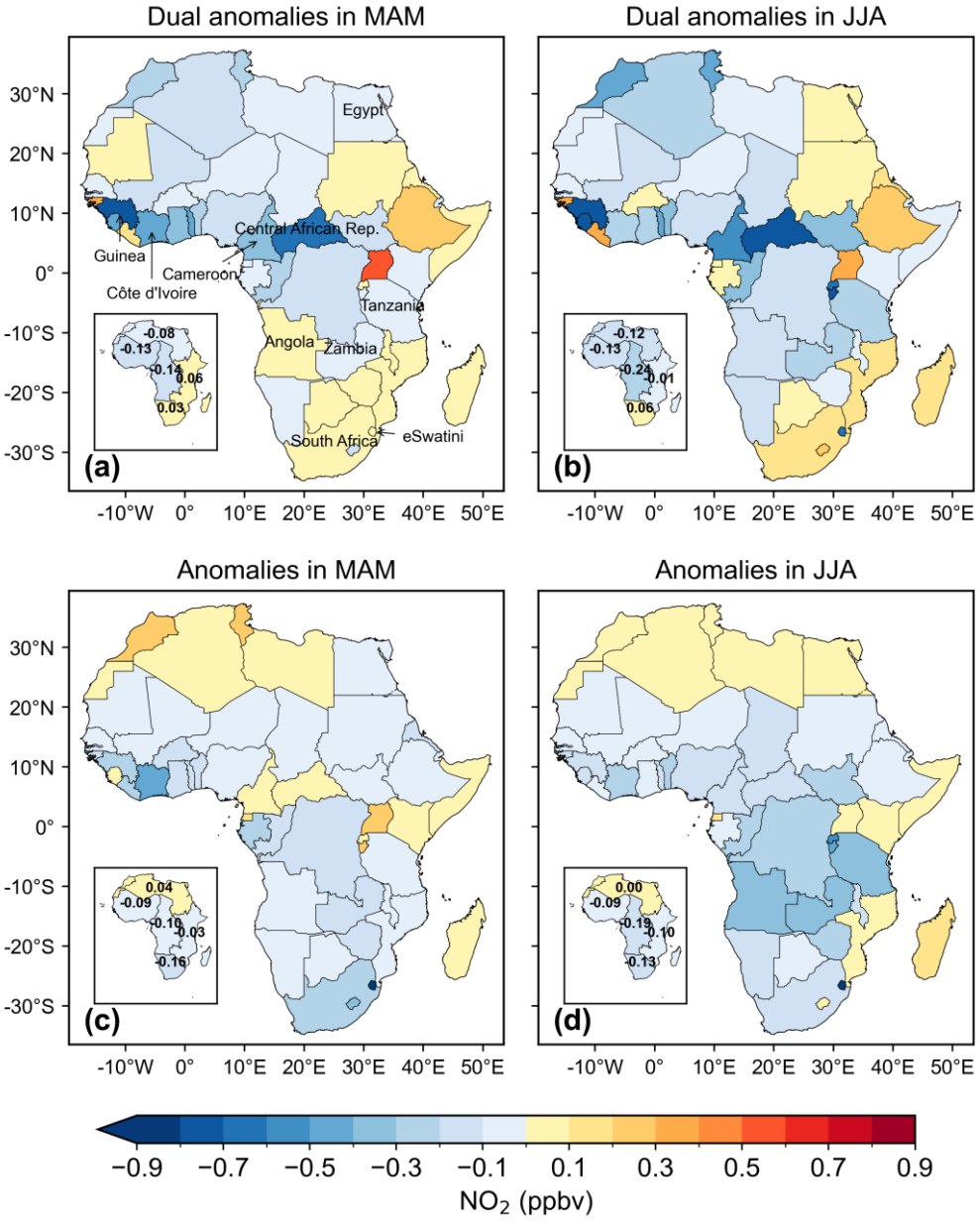

Figure 4: The same as Figure 2, but for NO_2. The units are ppbv.

As shown in Fig. 4, the spatial NO_2 anomalies in MAM and JJA estimated from the two methods agree well with each other, similar as we observed for CO. We attribute the reduction in NO_2 concentration in CA and WA regions to reduced biomass burning and industrial emissions due to strict lockdown measures as also discussed in previous studies (Fawole et al., 2022;

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Hickman et al., 2021). In most countries, the decreases in NO_2 during JJA were slightly larger than those during MAM, such as in the Central African Republic and Cameroon. This aligns with the overall trends in stringency index between the two seasons. In general, the average change in NO_2 across Africa during JJA is -0.09 ppb (-1.8 to 0.2 ppb, corresponding to a change rate of -29.9% to 30.1% depending on the country; see Fig. S31b), whereas during MAM, the average change is -0.05 ppb (-1.2 to 0.3 ppb, change rate between -38.8% and 23.4%). There are some countries that showed similar changes from both methods, such as Egypt, Chad, and Tanzania. In SA, the quarterly anomalies method showed an obvious decrease of NO_2 which were not captured by the quarterly dual anomalies method.

However, the countries showing the greatest declines differ between the two methods. The quarterly dual anomalies method shows the largest NO_2 decreases occur in WA and the northern parts of CA during MAM and JJA, such as in the Central African Republic (-0.6 and -0.8 ppbv), Cameroon (-0.3 and -0.5 ppbv), and Guinea (-0.8 and -0.7 ppbv). Conversely, quarterly anomalies method shows the greatest declines in NO_2 concentration in southern parts of CA and SA, such as eSwatini (-1.2 ppbv), South Africa (-0.3 ppbv), and Côte d'Ivoire (-0.4 ppbv) in MAM, and eSwatini (-1.8 ppbv) and Angola (-0.3 ppbv) in JJA. In addition, the quarterly dual anomalies showed NO_2 decreases in NA countries, such as Tunisia, Morocco, Algeria, and Libya, whereas the quarterly anomalies method showed an increase.

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3.1.3 SO_2 change

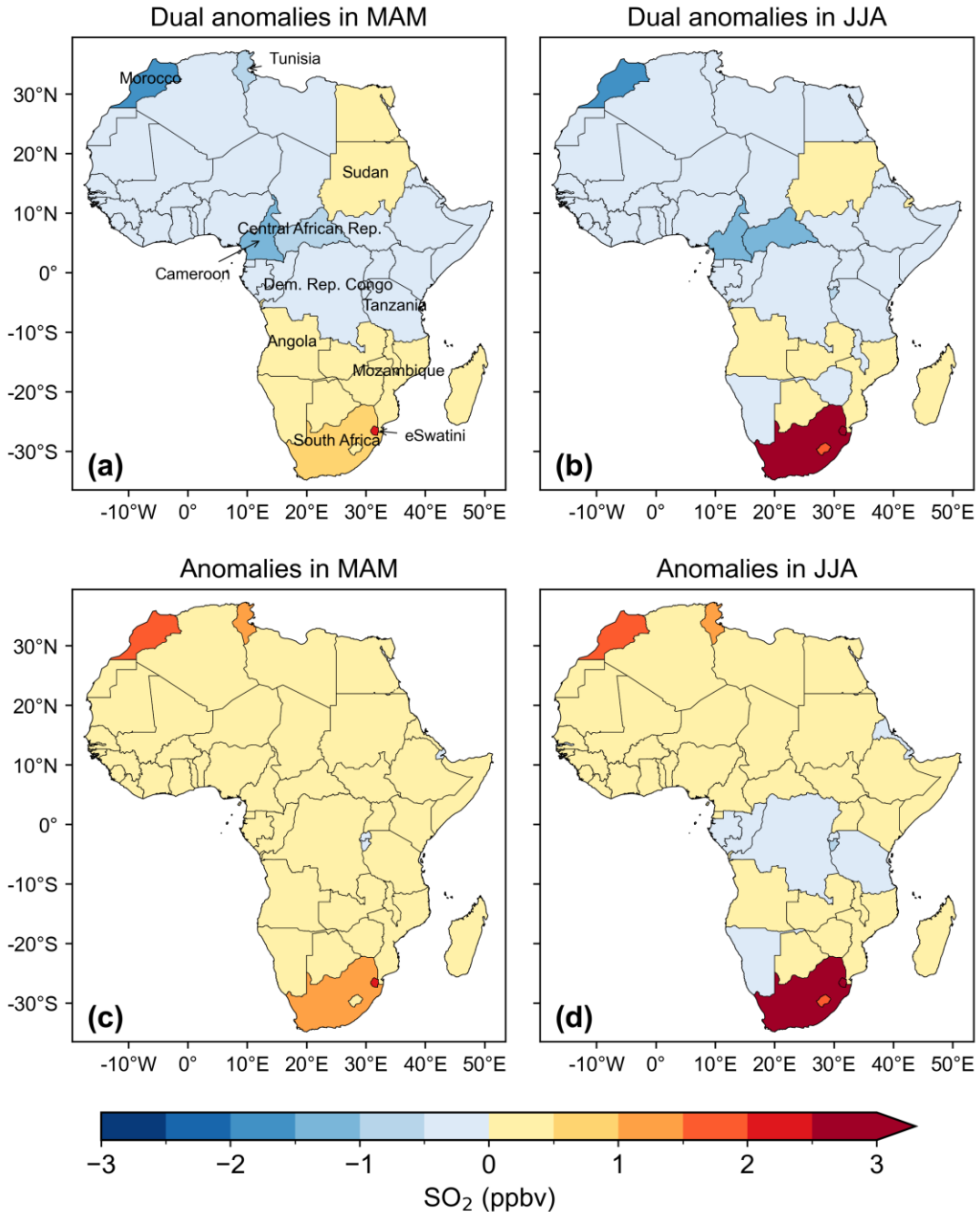

Figure 5: The same as Figure 2, but for SO_2.

Figure 5 illustrates the spatial distribution of SO_2 changes in MAM and JJA as estimated by two methods in African countries.

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Surprisingly, there is substantial and even contradictory variation in SO_2 concentration changes between the two methods. The dual quarterly anomalies methods showed a general decrease in SO_2 (Fig. 5a, b), leading by Morocco (-1.62 ppbv), Cameroon (-1.45 ppbv), and the Central African Republic (-1.21 ppbv). However, the quarterly anomalies indicate widespread increases in SO_2 concentration in both seasons (Fig. 5c, d), with slightly noticeable decreases in countries like the Democratic Republic of Congo and Tanzania during JJA. We attributed this difference as the quarterly anomalies method indicates the rate changes at which the concentration of pollutants decreases or rises during the lockdown period compared with those during pre-lockdown, and we found higher SO_2 concentration in the WA and NA in Feb, 2020, which makes the relative comparisons with MAM and JJA in 2020 much lower. However, the anomalies method only considered the changes between the months in 2020 with corresponding months in years.

In addition, both methods indicated that in SA countries such as South Africa and Mozambique, the concentration of SO_2 continued to increase, which contradicts with the stringency index change. We attributed this increases to the possible expansion of coal-fired power plants in these countries (Dahiya et al., 2020; Agbo et al., 2021). On April 1st, 2020, this region doubled the emission limit for SO_2 from coal-fired power plants and allowed many factories to reopen after July 1st (Dahiya et al., 2020; Hale et al., 2021). Besides, the stay-at-home policy may actually increase residential electricity demand and residential fuel (Matandirotya et al., 2022; Adesina et al., 2022; Hersey et al., 2015), thereby increasing the operating load of power plants (Wetchayont and Levy, 2021) and then SO_2 concentrations. Meanwhile, the dry, cold conditions in the southern Hemisphere make it harder for SO_2 to disperse. Previous studies have observed that, apart from Africa, in some countries with high SO_2 emissions such as Turkey (Kotan and Erener, 2023) and India (Mor et al., 2021), certain cities also experienced an increase in SO_2 concentrations during lockdown periods (Mor et al., 2021; Mahato et al., 2020; Qayyum et al., 2023). This highlights the need for stricter coal restriction policies or promoting the use of clean energy to reduce environmental pollution in these regions. Therefore, containment policies implemented in winter may have a limited effect on SO_2 reduction in regions with heavy coal-burning industries and residential burnings.

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290 **3.2 Ozone change**

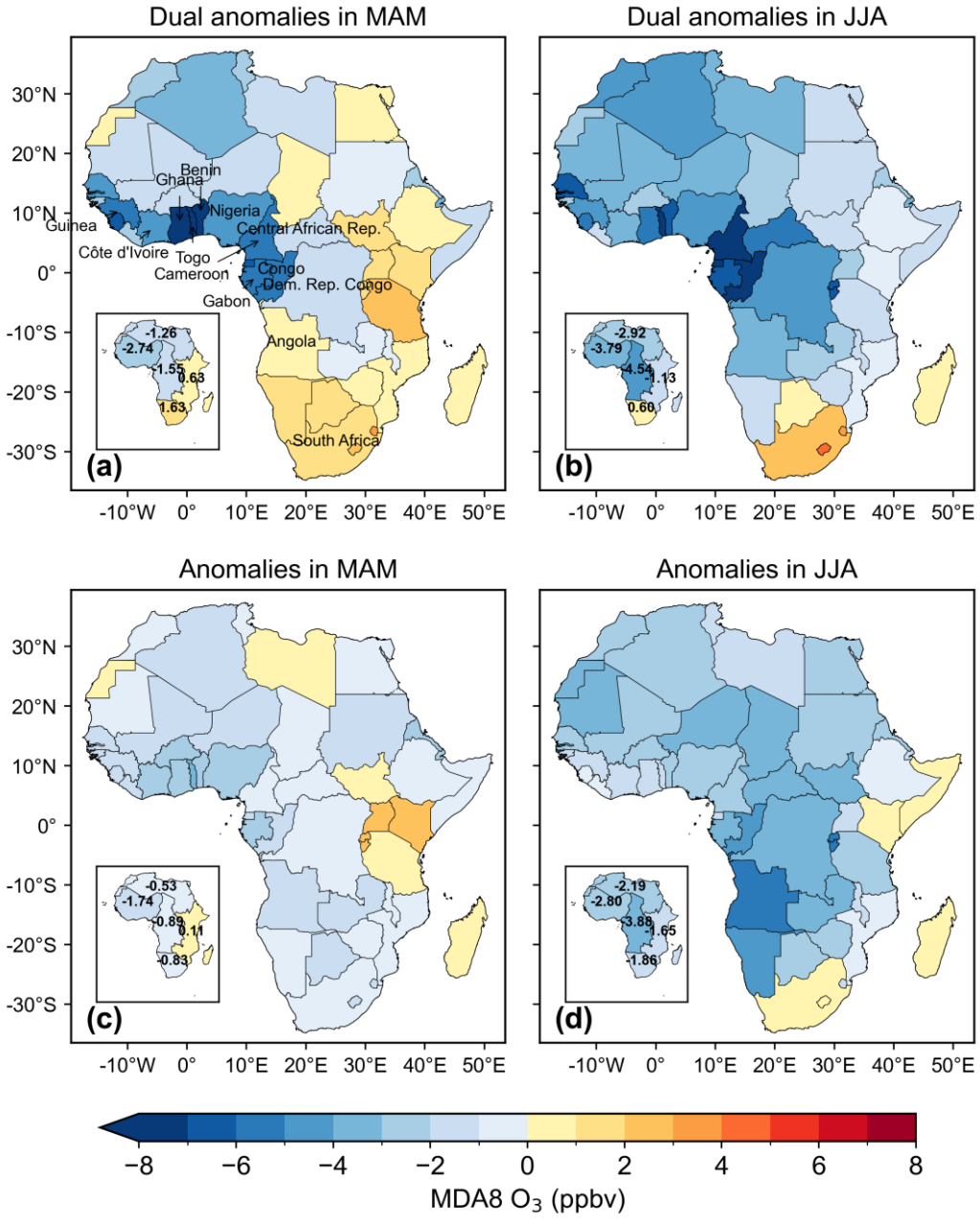

Figure 6: The same as Figure 2, but for MDA8 O_3.

As shown in Fig. 6, both methods indicated a larger decline for the maximum daily 8-hour average (MDA8 O_3) in African
295 during JJA that those during MAM. The JJA anomaly is -2.48 ppb (-5.98 to 0.35 ppb), ranging from -11.67% to 1.08%,

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compared with an -0.74 ppb (-3.12 to 2.74 ppb, ranging from -10.99% to 7.54%) decreases in MAM (Fig. S32). Both methods agree with each other on the regions with the greatest declines. During MAM, the largest declines occur in the WA region, such as Togo (-9.37 from the dual anomaly method, and -3.12 ppbv for the anomaly method), Benin (-7.66 and -2.92 ppbv), and Ghana (-7.56 and -2.96 ppbv). In JJA (Fig. 6b, d), countries in the CA exhibit the most significant decreases, including Congo (-7.64 and -4.57 ppbv for dual anomaly and anomaly method respectively), Gabon (-6.03/-3.59 ppbv), and Central African Republic (-5.40/-3.47 ppbv). In regions with frequent biomass burning such as WA and CA, the decline in O_3 concentrations may be more closely related to reduced biomass burning emissions due to lockdown measures. We employed the ratio of satellite derived HCHO (representing VOCs) to NO_2 as an indicator to assess O_3 sensitivity to precursors in Africa (Nussbaumer et al., 2023; Choi et al., 2012; Duncan et al., 2010). We found that in many countries across WA, Central, and EA, such as Togo, Ghana, and Benin, anomalies in O_3 concentrations corresponded well with changes in NO_2 (Fig. 7). This alignment is attributed to higher levels of VOC/NO_x ratios in regions abundant in tropical vegetation, where O_3 tends to correlate positively with NO_x.

In South Africa, both methods showed a greater increase in O_3 concentrations during the JJA compared to MAM (Fig. 6), which may be associated with a decline in NO_2 concentrations. According to Fig. 7, during the JJA, industrial areas of South Africa exhibited broader ranges of lower HCHO/NO_2 ratio, indicating a negative correlation between O_3 and NO_x (Laban et al., 2018). Significant reductions in NO_x levels favors O_3 formation (Wang et al., 2019). Additionally, strong correlations between O_3 and CO in South Africa have been reported (Borduas-Dedekind et al., 2023), and Vakkari et al. (2020) documented rapid O_3 formation in plumes from grassland fires in South Africa, highlighting the substantial influence of biomass burning emissions on O_3 generation in SA. The O_3 increases during the lockdown were also seen in some regions of other countries, such as Shanghai (Tan and Wang, 2022), North China (Liu et al., 2021) and Milan in Italy (Zoran et al., 2020).

In both methods, a widespread decrease in surface O_3 across NA was observed, possibly influenced by ozone precursors and meteorological conditions, particularly temperature (Tang et al., 2021). Comparing with previous years, temperatures in the Sahara have notably decreased, particularly during JJA, with coastal regions experiencing a decline of 4°C (Fig. S27c). Lower temperatures might reduce the photolysis rate of ozone molecules, further stabilizing the atmosphere and making it less likely for O_3 to disperse, thereby leading to decreased surface O_3 concentrations.

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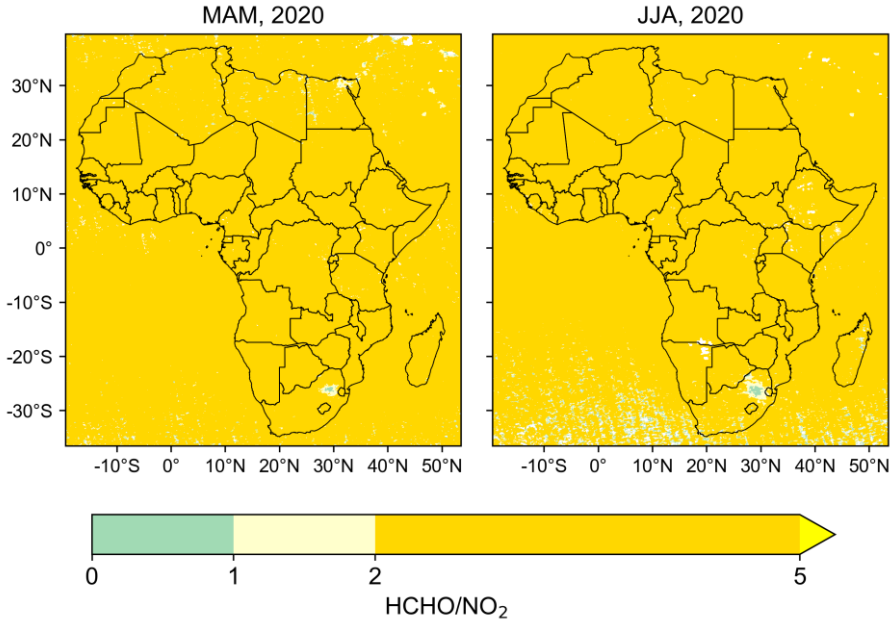

Figure 7: Spatial distribution of averaged HCHO/NO_2 ratios during MAM and JJA, 2020.

3.3 Aerosol particles

The inorganic aerosols concentration changes, including sulfate, nitrate, ammonium aerosols, often exhibit nonlinear relationships due to their formation through both primary emissions and secondary reactions of gaseous precursors in the atmosphere (Gao et al., 2003). Etchie et al. (2021) found that meteorological conditions rather than lockdowns resulted in marginal reductions in aerosol levels in Nigeria. Similar observations of no significant reductions in atmospheric particulate matter due to lockdown measures have also been reported in China, United States, Spain, and India (Le et al., 2020; Li et al., 2021; Baldasano, 2020; Chen et al., 2020b; Vig et al., 2023).

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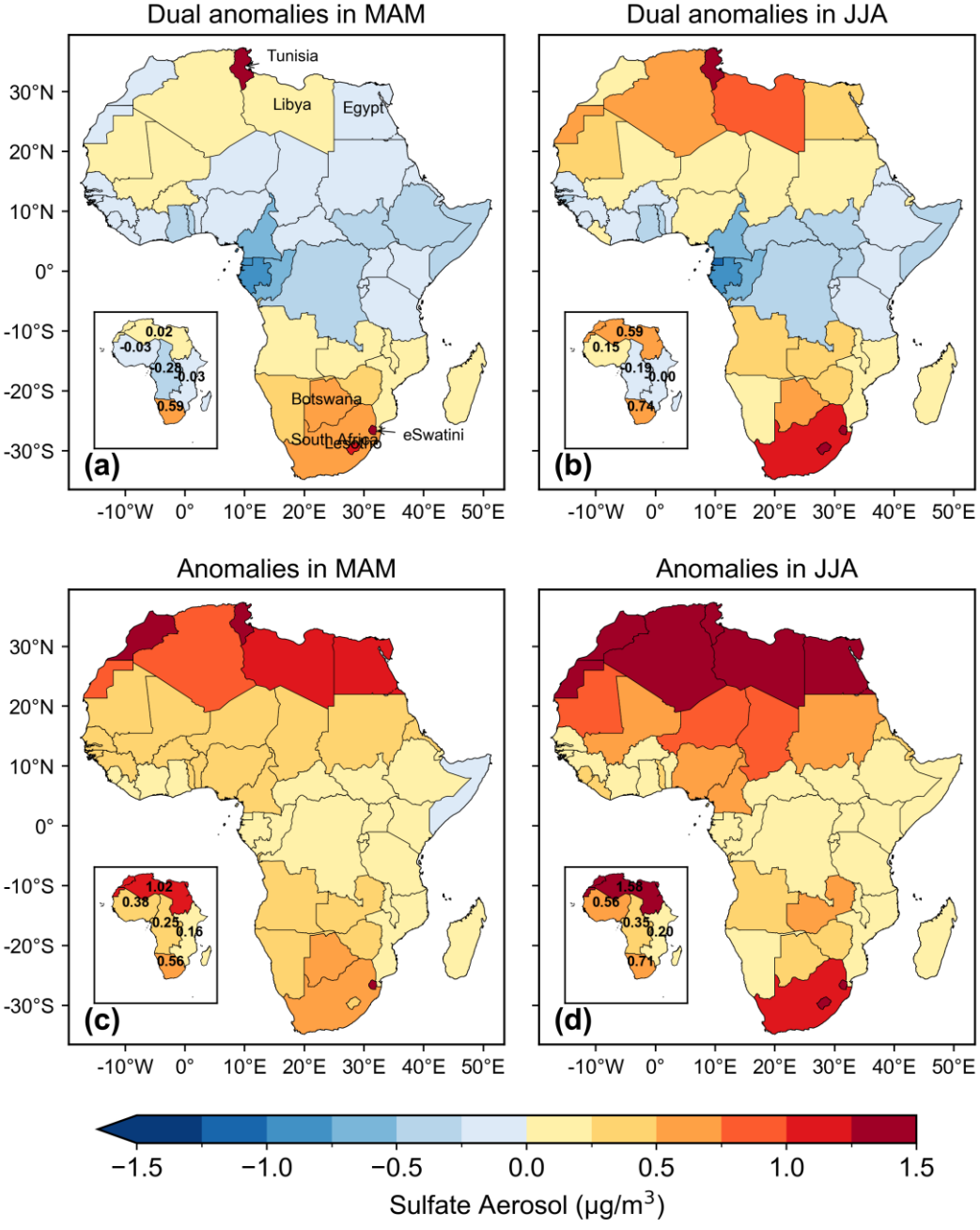

Figure 8: The same as Figure 2, but for sulfate aerosol.

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Unlike other pollutants, both methods showed a greater increase for sulfate aerosols in JJA compared to MAM across Africa overall especially in NA and SA (Fig. 8). We estimated that the average sulphate aerosol particles in Africa were 0.49 μg/m^3 and 0.72 μg/m^3 for MAM and JJA respectively from the quarterly anomaly method (Fig.S34). NA, located in the Sahara Desert,

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is the world's largest dust source (Huneeus et al., 2011). The increase in sulfate aerosol concentration was primarily influenced by Saharan dust pollution in June 2020 (Burgess and Oyola-Merced, 2024). Furthermore, the decrease in temperature during the JJA in NA regions compared to previous years also may favors the accumulation of aerosols (Lou et al., 2017; Singh et al., 2020a), thereby increasing aerosol particle concentrations. In SA, the significant increase in sulfate, particularly in South Africa, may be linked to increased coal combustion activities during lockdown periods. However, we also noticed that the two methods showed distinct results for sulfate aerosol changes in WA, CA, and EA regions, similar as we observed for the gaseous SO_2 (Fig. 5). The quarterly dual anomaly displayed an overall decrease in concentrations in these regions (Fig. 8a, b), whereas the quarterly anomaly shows a slight increase (Fig. 8c, d). This is linked to the elevated February concentrations of sulfate aerosols near the equator compared to previous years (Fig. S8d). The comprehensive analysis of both methods suggests that despite a relative increase in sulfate aerosol concentrations compared to previous years (Fig. S8 a,d), reduced fires due to pandemic lockdowns or meteorological conditions can mitigate the upward trend in sulfate concentrations. Similar to sulfate aerosol, we observed an increases of ammonium aerosol in both MAM and JJA in most countries (Fig. 9), especially in the NA and SA regions. We concluded that that ammonium existed mostly in the format of sulfate ammonium (Bhanarkar et al., 2005; Fattorini and Regoli, 2020), and was therefore influenced by biomass burning and soil emissions (e.g., animal manure, fertilizers) (Mor et al., 2021; Gordon et al., 2023).

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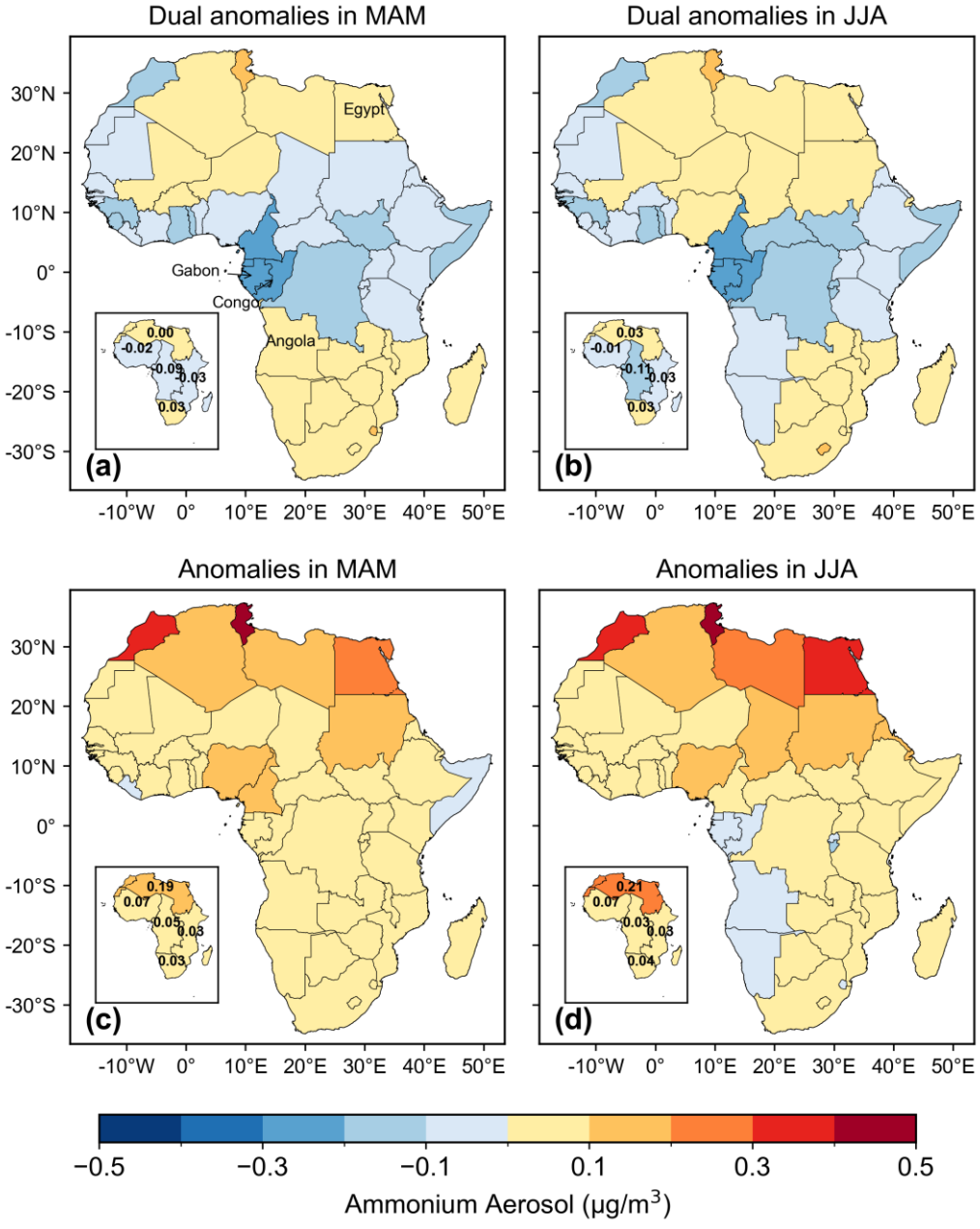

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Figure 9: The same as Figure 2, but for ammonium aerosol.

As shown in Fig. 10, unlike sulfate and ammonium aerosols, the nitrate aerosol showed consistent decreases from the two methods in major African countries. For instance, using the quarterly anomalies method, the average MAM anomaly in Africa
360 is -0.01 μg/m³, ranging from -0.23 to 0.06 μg/m³ (-89.45% to 114.27%, Fig. S36), while the JJA anomaly is -0.04 μg/m³,

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ranging from -0.64 to 0.004 μg/m³ (-74.50% to 47.22%). Both methods showed a greater decrease in JJA compared to MAM across Africa, particularly in countries such as Angola, Zambia, and eSwatini. Relative to other aerosol particles, nitrate aerosol particles primarily depend on emissions of nitrogen oxides from human activities in the atmosphere, such as traffic, industrial activities, and construction (Agbo et al., 2021). Therefore, during the pandemic, restrict traffic measures from lockdown lead to more pronounced reductions in nitrogen dioxide levels, thereby affecting nitrate aerosol production. In regions with higher nitrate, such as Egypt, Tunisia, and Angola (Fig. S9), the magnitude of concentration decrease was also greater, consistent with previous findings (Mostafa et al., 2021). We observed that in some countries with lower stringency index of lockdown measures (such as below 60), including Niger, Burkina Faso and Ethiopia, pollutant concentrations decreased slowly or even increased. This suggests that in Africa, the wide-ranging decrease in nitrate aerosol concentrations due to lockdown measures may not have been uniformly observed.

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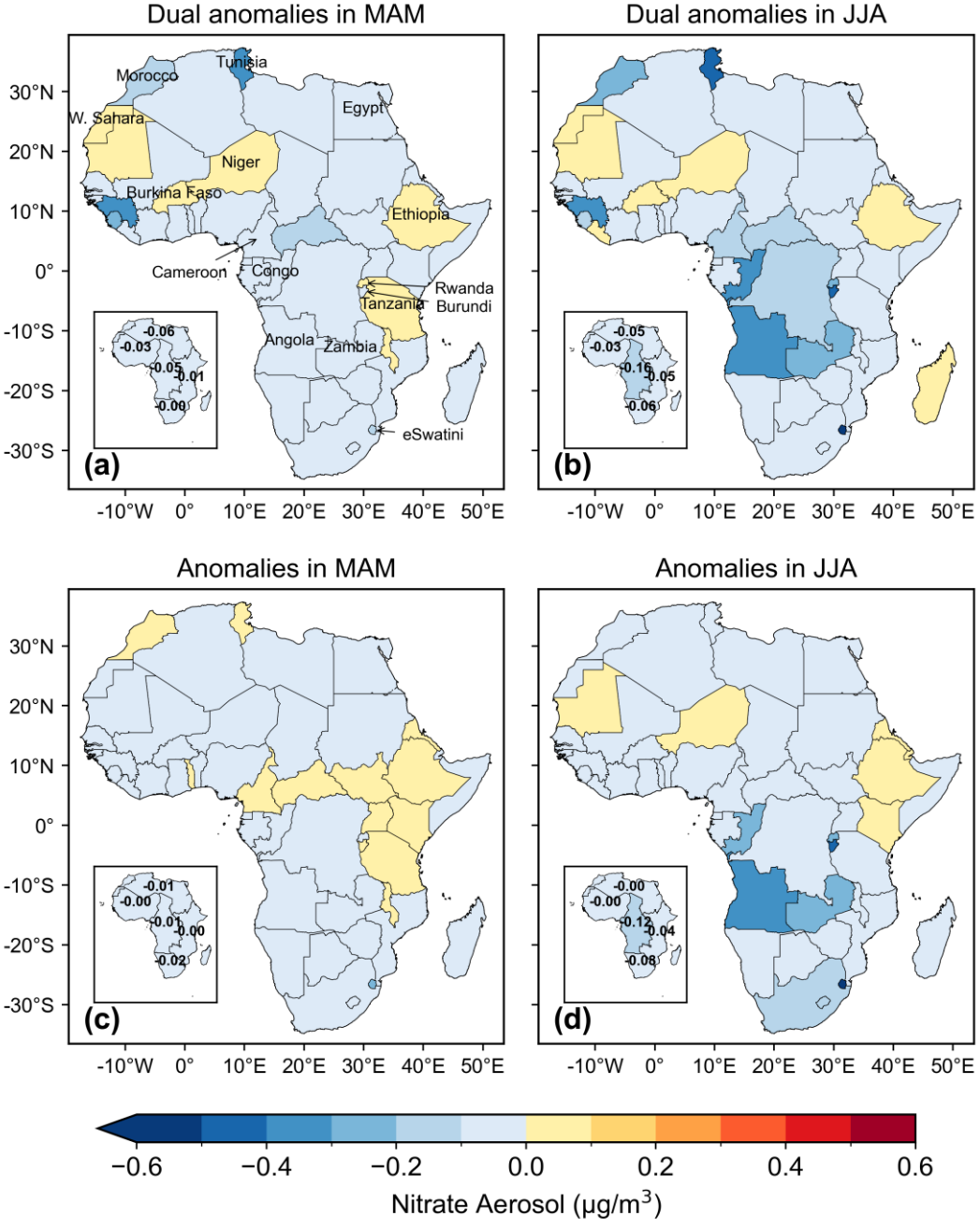

Figure 10: The same as Figure 2, but for nitrate aerosol.

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4 Summary and conclusions

This study analyzed the impact of lockdown policies on the changes of gaseous pollutants in African countries, focusing on CO, NO_2, SO_2, O_3, and aerosols particles. We applied two distinct methods, quarterly dual anomalies and quarterly anomalies to calculate the concentration changes in MAM (March to May) and JJA (June to August) in 2020. The quarterly dual anomalies calculated the air quality changes during the lockdown period compared with the pre-lockdown period (February), and then compared these changes to corresponding periods from reference years (2005 - 2019). The quarterly anomalies calculated the seasonal concentrations differences between 2020 and the multi-year mean (2005 - 2019) for MAM and JJA individually.

1. Both methods revealed decrease in CO concentrations in majority African countries, with greater reductions observed during JJA compared to MAM. We attributed this to the emissions reductions from biomass burning (sub-Saharan) and the transport emissions (Saharan) which was both caused by the restricted human activities during the lockdown (Hua et al., 2024; Mostafa et al., 2021). The random forest model further corroborated the significant role of anthropogenic emission changes in the observed reduction of CO concentrations in CA.
2. Both methods observed a decrease in NO_2 concentrations across most African countries, with a slightly larger reduction in JJA compared to MAM, demonstrating the effectiveness of restrictions on traffic, biomass burning, and industrial activity. However, discrepancies were observed in the NA region, where the quarterly dual anomalies method indicated a decline in NO_2, while the quarterly anomalies method showed an increase. This suggests that while NO_2 levels were generally higher in February 2020 compared to previous years, the containment measures, especially traffic restrictions (Mostafa et al., 2021) mitigated the rate of increase.
3. Unexpectedly, both methods observed an increase in SO_2 in South Africa, especially during JJA. This increase may be linked to relaxed emission limits for factory pollutants and heightened coal-fired power plant usage during home isolation in winter (Dahiya et al., 2020; Hale et al., 2021). For most other countries, the quarterly dual anomalies method revealed a general decline in SO_2, whereas the quarterly anomalies indicated an increase. This shows that despite an overall increase in SO_2 levels in 2020, containment measures may have slowed the rate of increase.
4. Regarding MDA8 O_3, both methods indicated a general decline in concentrations in most countries, especially in WA and CA regions, with greater reductions observed during JJA. This decline is likely related to reduced emissions from biomass combustion as a result of lockdown measures. However, in South Africa, a more significant increase in O_3 during JJA was noted, potentially due to decreased NO_2 concentrations and lower tropospheric $HCHO/NO_2$ ratios.
5. Both methods revealed an increase in sulfate and ammonium aerosols in the NA and SA regions, with a larger increase during JJA. In the NA region, this increase is likely associated with an extreme dust event in June 2020, while in the SA region, it corresponds to increased coal burning (Simelane and Langerman, 2023). Nitrate aerosols consistently decreased across both quarters, reflecting the overall reduction in NO_2 emissions due to containment measures.

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In conclusion, the air quality changes during lockdown in Africa may be interweaving with both natural and anthropogenic influences. Judging the similarities and disagreements from the two methods applied in this study, we highlight the necessity to include more surface observations for African countries, as well as stricter emission standards for coal-fired plants and promote clean energy infrastructures.

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Author contributions: YZ and ZH designed the study; KZ and ZH acquired the data, ZH performed data analysis, prepared the plots and tables, wrote the paper with the help from ZL, ZW, BL. All authors conducted research and wrote and edited this manuscript.

Competing interests: The authors declare that they have no competing interests.

Data and materials availability: All the data required to assess the conclusions in the paper are present within the paper and/or supplementary materials. The baseline concentration and emission data used in the study can be freely downloaded from NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) (https://disc.gsfc.nasa.gov/information/data-release?title=Release%20of%20TROPESS%20Chemical%20Reanalysis%20Products, last accessed September10th, 2024).

Appendix A. Supporting Information

Supplementary figures and tables associated with this article can be found in the online version at....

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