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Air Quality Improvement from COVID-19 Lockdown in the East African Community: Evidences from Kampala and Nairobi Cities

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Abstract

A novel highly infectious disease (Corona virus disease-2019, COVID-19) has been an unprecedented global crisis. Following COVID-19 break out from Wuhan to the rest of the world, various countries adopted partial or total lockdowns to curb its progression or mitigate it. Lockdowns left drastic effects on health, physiological, social, economic and environmental fronts. This study reports on the impacts of COVID-19-induced human mobility restrictions on atmospheric levels of nitrogen dioxide (NO_2) and particulate matter represented in absorbing aerosol index (AAI) in Kampala, Nairobi and Dar es Salaam cities of Uganda, Kenya and Tanzania in the East African Community. Using satellite data, it was found that NO_2 emissions decreased by about 6.0% and 8.91% in Kampala and Nairobi whereas AAI decreased by about 1.91% in 2020. In Dar es Salaam, NO_2 emissions increased by about 1.16% while the AAI remained almost constant in the same period. It is concluded that although there were substantial reductions in air pollution during 2020 (particularly the COVID-19 lockdown periods) in Kampala and Nairobi, these are not sustainable and deterioration of air quality after lifting of the restrictions has started to occur. Therefore, legislative actions need to be upheld to maintain air quality within the recommended levels.

Subject Areas

Environmental Chemistry, Air Pollution

Keywords

Absorbing Aerosol Index, Nitrogen Dioxide, Particulate Matter, Corona Virus Disease-19 (COVID-19)

1. Introduction

The Coronavirus disease-2019 (COVID-19) pandemonium has been a tragedy with outlasting aggregate health, environmental and economic impacts globally [1]. COVID-19, whose causative virus is a positive-sense single-stranded RNA β-coronavirus (SARS-CoV-2) is highly infective [2] as evidenced by its rapid spill over to the rest of the world from China between December 2019 and March 2020 [3]. It was first appreciated among a cluster of 27 pneumonia-like case patients in the Chinese city of Wuhan (Hubei province) on 12th December 2019 before it gripped onto the rest of the world. The virus marks the seventh incidence of coronaviruses ever reported in human history. COVID-19 was declared a Public Health Emergency of International Concern on January 30th, 2020 by the World Health Organization [4] before it was finally announced as a pandemic on March 22nd, 2020 [5]. To curb the spillage of the ill-fated virus, most countries initially imposed lockdowns and restricted international flights, which paralyzed most industrial activities. As of 1st February 2021, at least 2,222,647 mortalities and 102,584,351 confirmed cases of COVID-19 had been reported globally, with the United States of America in the lead of the highest number of reported cumulative cases [6].

The East African Community (EAC), just like the rest of the world suffered the brunt of COVID-19 which reached it by importation. Kenya was the first to record its coronavirus case on 12th March 2020, followed by Rwanda and Tanzania on 14th and 16th March 2020, Uganda on March 21st, 2020 while Burundi and South Sudan registered their first cases on 25th March 2020 and 5th April 2020 [7]. Of these countries, Rwanda and Uganda initially contained the pandemic quite well, compared to others. As of 1st February 2021 (the time of this writing), at least 161,726 confirmed cases, 112,742 recoveries and 2370 mortalities due to COVID-19 have been reported in the EAC [8].

The EAC embraced COVID-19 containment measures including mandatory institutional and self-quarantines, social distancing, restriction of international flights to and from high-risk countries, reduction of economic and social activities i.e. lockdowns and curfews. Rwanda was the first country in the EAC and Sub-Saharan Africa at large to implement total lockdown on 17th March 2020. This was later followed by Uganda on 31st March 2020 as a presidential strategy to curb the pandemic spread. Kenya imposed initially a partial lockdown on 6th April 2020 but later extended it to a total lockdown as COVID-19 cases increased [7]. This study reported on the impacts of the pandemic-induced human mobility restrictions on atmospheric levels of nitrogen dioxide emissions and particulate matter represented in absorbing aerosol index in Kampala, Nairobi and Dar es Salaam cities of the EAC.

2. Methods

2.1. Study Area and Selection of Studied Cities

The current study was undertaken in the EAC, a consortium of countries forming one of the developing communities of the world. It is a regional intergovernmental organization of six (6) partner states (**Figure 1**) in the African Great Lakes region of Eastern Africa namely: Uganda, Kenya, Rwanda, Tanzania, Burundi and South Sudan. Its headquarters is in Arusha, Tanzania [9].

As outliers with Burundi among the East African responses to COVID-19 pandemic, Tanzania (Dar es Salaam) was considered in this study as a reference rather than a case study. The two countries (Uganda and Kenya) have been chosen because the former enforced a complete lockdown earlier while the latter started with a partial lockdown followed by a total lockdown. The major determining factors for the choice of these countries were because they were the only countries in the EAC for which nitrogen dioxide (NO_2) emissions satellite data were available from National Aeronautics and Space Administration (NASA) database.

Figure 1. Map of East African Community showing member countries with the cities under study.

2.2. Study Design

This study used satellite monitoring measurements for air pollutants recorded from the onset of COVID-19 in January 2020 through partial to complete COVID-19 lockdowns until December 2020 in the EAC. The baseline period used were the years 2015-2019 for nitrogen dioxide emissions and 2019 for the absorption aerosol index. We adopted this approach because the faculty of satellite devices in remote sensing of the lower troposphere has improved considerably over the years. Aerosol factors, for instance, are verifiable on spatial scales of a few kilometers using the space-borne radiometers [10]. Further, nitrogen dioxide along with other trace gases can be effectively identified on urban levels using spectrometers [10]. Unlike field monitoring stations that forecasts only vacillations in air quality or assess emissions at discrete points, satellite monitoring offsets this drawback with its faculty to model horizontal transportation of air pollutants for both long- and short periods [11]. This singular aspect, enhances greatly, synoptic and geospatial knowledge of ground-based air quality data [11]. In this context, data from satellite monitoring can be harnessed for establishing regions with the highest concentrations or furnishing warnings of upcoming air quality events such as wildfires and dust storms. Another advantage conferred by satellite systems is supplying air quality information for regions devoid of surface-based monitors [11].

2.3. Nitrogen Dioxide Measurement

In this study, changes in NO_2 emissions before and during the COVID-19 pandemic year of 2020 were monitored by following Aura satellite data [12]. NASA launched Aura satellite on July 15th 2004. It is equipped with an ozone monitoring instrument (OMI) to monitor the changes in air quality for various regions worldwide [13]. The OMI satellite instruments precisely detect air pollutants such as NO_2, ozone, sulfur dioxide, carbon monoxide and methane [14]. The tools compute backscattered radiations from the sun in a broad spectral range from ultraviolet (UV) to infrared wavelengths. Advanced retrieval algorithms are thereafter applied to transform the measured radiation to pollutant concentrations, such as a tropospheric column density of NO_2 [15].

2.4. Absorbing Aerosol Index

The absorbing aerosol index (AAI) data for 2019 and 2020 were obtained from Tropospheric Emission Monitoring Internet Service [16] of the European Space Agency (ESA).

2.5. Data Analysis

Data retrieved from satellite monitoring assessments during the COVID-19 pandemic lockdown were compared with both statutory and international air quality compliance standards.

3. Results and Discussion

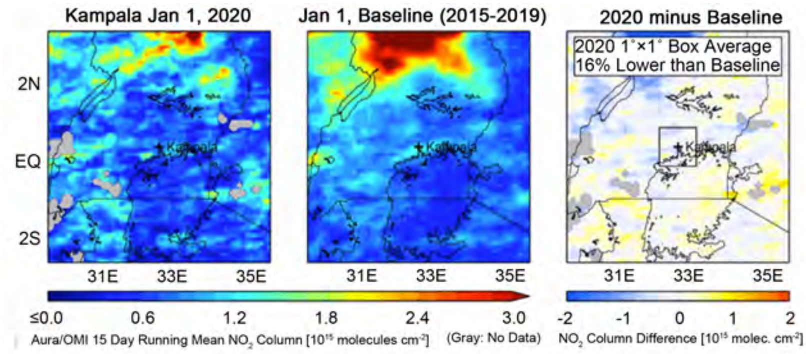
3.1. Changes in Nitrogen Dioxide Emissions

Data for NO_2 emissions were retrieved from OMI for January 2020 to December 2020 and the baseline years (2015-2019). Data for the targeted months (March, April and May) in 2020 represents the peak of the pandemic with total or partial lockdowns in Uganda and Kenya, while Tanzania had no such containment measure in the same period. Comparison of the data for each month in 2020 with those of the previous five years (2015 to 2019) aimed at logically identifying whether the implemented containment measures during COVID-19 outbreak had an effect on NO_2 emissions in Uganda and Kenya or not. In **Figures 2-4**, the darker the color, the higher NO_2 concentration/emission is [15] [17].

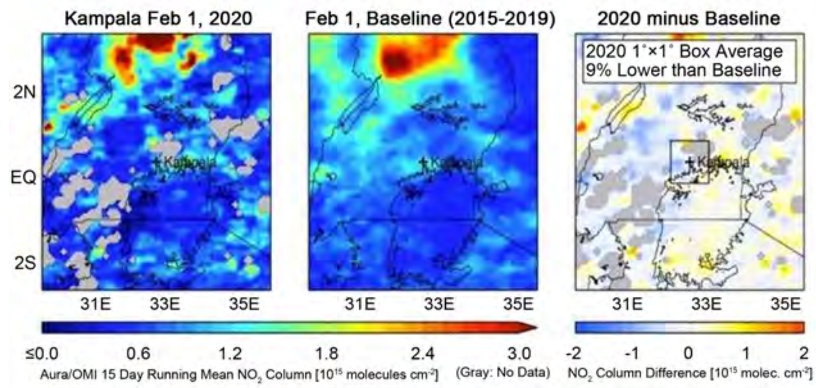
Data retrieved indicated that 2020 NO_2 emissions in Kampala and Nairobi were lower than the average levels in the respective cities during the same months in 2015-2019. It is clearly observed that the orange colors in **Figure 2** and **Figure 3** are darker for 2020 than for 2015-2019, indicating there was a reduction in NO_2 emissions in 2020 during the COVID-19 pandemic.

A percentage difference was calculated inside a $1^\circ \times 1^\circ$ box over Kampala (**Figure 2**). In January 2020, NO_2 emissions in Kampala were 16% lower than the baseline. This could be due to the reduced movements during the festive season. In February 2020, NO_2 emissions were only 9% lower than the baseline in Kampala. This is because during February, most schools and tertiary institutions had reopened, which translates into increased vehicular movements. By March 18th 2020 when total lockdown along with other containment strategies were adopted in Uganda to reduce the spread of COVID-19 [18] [19] [20], NO_2 emissions over Kampala dropped by about 2% compared with the baseline period (**Figure 2(c)**). From April 1st 2020 to May 1st 2020, NO_2 emission over Kampala reduced by 12% and 3%, respectively. The lower percentage reduction in May 2020 could be because the government eased some restrictions despite maintaining lockdown in late April and early May [21] [22]. This also explains the lower percentage reductions in NO_2 emissions (10%, 3%, 17%, 0%, 6% and 8%) lower than the baseline recorded between June and November 2020, as the government allowed vehicular movements with restricted number of passengers (carrying half their capacity), reduced curfew hours and removed total lockdown, and allowed resumption of work and commercial activities to reduce risks of economic recession [23] [24]. In December 2020 (**Figure 2(l)**), NO_2 emissions in Kampala was 8% greater than the baseline. This could be in addition to the foregoing reasons, increased movements in preparation for the festive season (Christmas celebration on 25th December 2020 and New Year celebration on 1st January 2021) as well as increased campaign activities in preparation for elections which occurred from 14th January 2021 up to early February 2021.

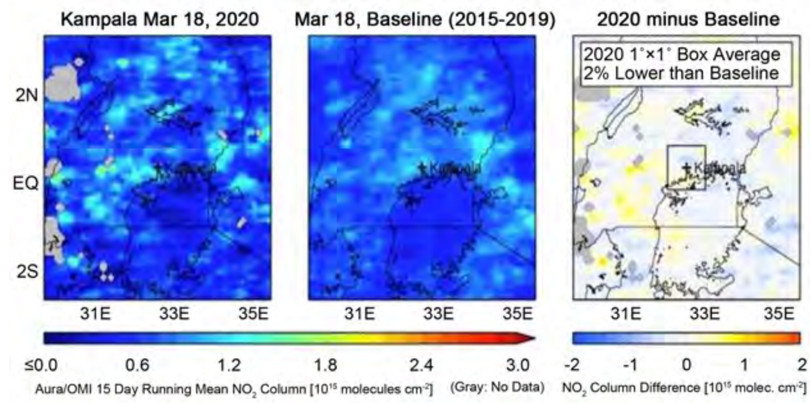
For Nairobi (Kenya), a percentage difference was calculated inside a $1^\circ \times 1^\circ$ box over it. As depicted in **Figure 3**, NO_2 emissions were 18% greater than the baseline in January 2020 but this increased to 20% lower than the baseline in


Kampala Jan 1, 2020
Jan 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
16% Lower than Baseline
2N
EQ
2S
31E 33E 35E
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO_2 Column [10^{15} molecules cm^{-2}]
(Gray: No Data)
NO_2 Column Difference [10^{15} molec. cm^{-2}]

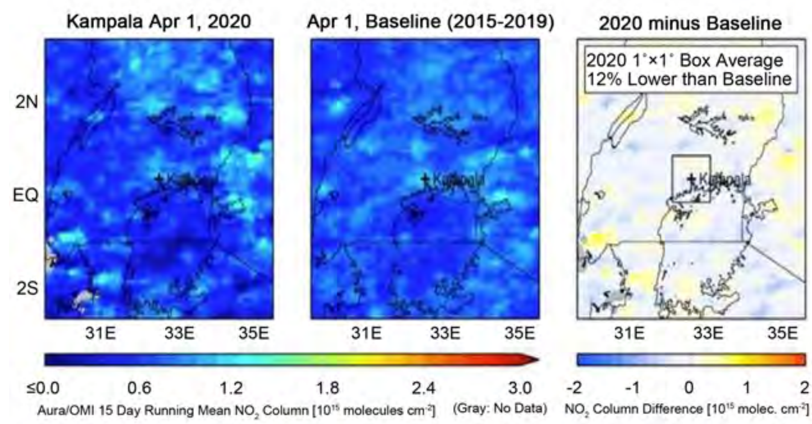
(a)


Kampala Feb 1, 2020
Feb 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
9% Lower than Baseline
2N
EQ
2S
31E 33E 35E
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO_2 Column [10^{15} molecules cm^{-2}]
(Gray: No Data)
NO_2 Column Difference [10^{15} molec. cm^{-2}]

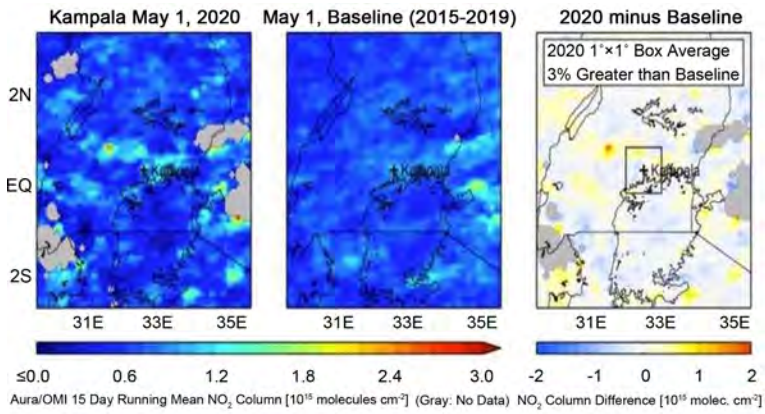
(b)


Kampala Mar 18, 2020
Mar 18, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
2% Lower than Baseline
2N
EQ
2S
31E 33E 35E
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO_2 Column [10^{15} molecules cm^{-2}]
(Gray: No Data)
NO_2 Column Difference [10^{15} molec. cm^{-2}]

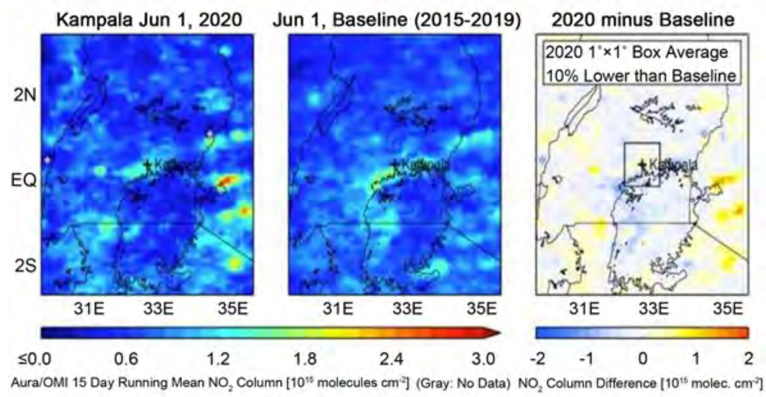
(c)


Kampala Apr 1, 2020
Apr 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
12% Lower than Baseline
2N
EQ
2S
31E 33E 35E
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO_2 Column [10^{15} molecules cm^{-2}]
(Gray: No Data)
NO_2 Column Difference [10^{15} molec. cm^{-2}]

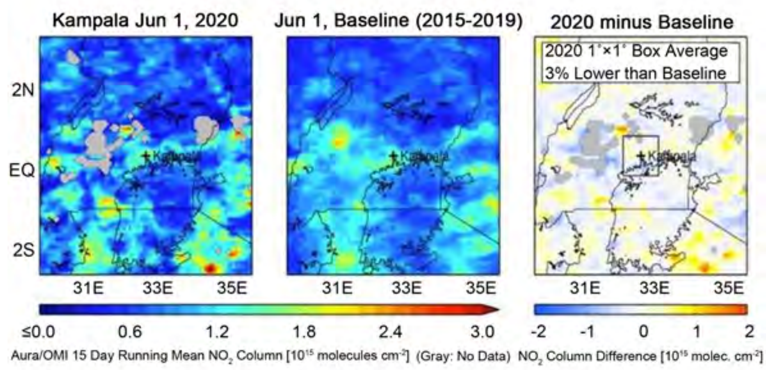
(d)


Kampala May 1, 2020
May 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
3% Greater than Baseline
2N
EQ
2S
31E
33E
35E
≤0.0
0.6
1.2
1.8
2.4
3.0
-2
-1
0
1
2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

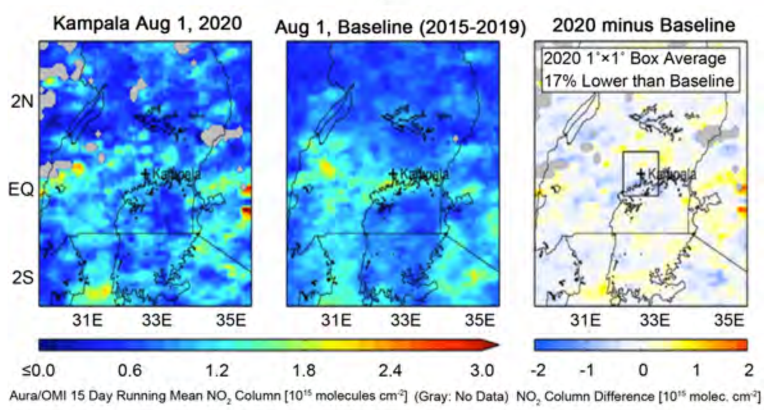
(e)


Kampala Jun 1, 2020
Jun 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
10% Lower than Baseline
2N
EQ
2S
31E
33E
35E
≤0.0
0.6
1.2
1.8
2.4
3.0
-2
-1
0
1
2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

(f)


Kampala Jun 1, 2020
Jun 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
3% Lower than Baseline
2N
EQ
2S
31E
33E
35E
≤0.0
0.6
1.2
1.8
2.4
3.0
-2
-1
0
1
2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

(g)


Kampala Aug 1, 2020
Aug 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
17% Lower than Baseline
2N
EQ
2S
31E
33E
35E
≤0.0
0.6
1.2
1.8
2.4
3.0
-2
-1
0
1
2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

(h)

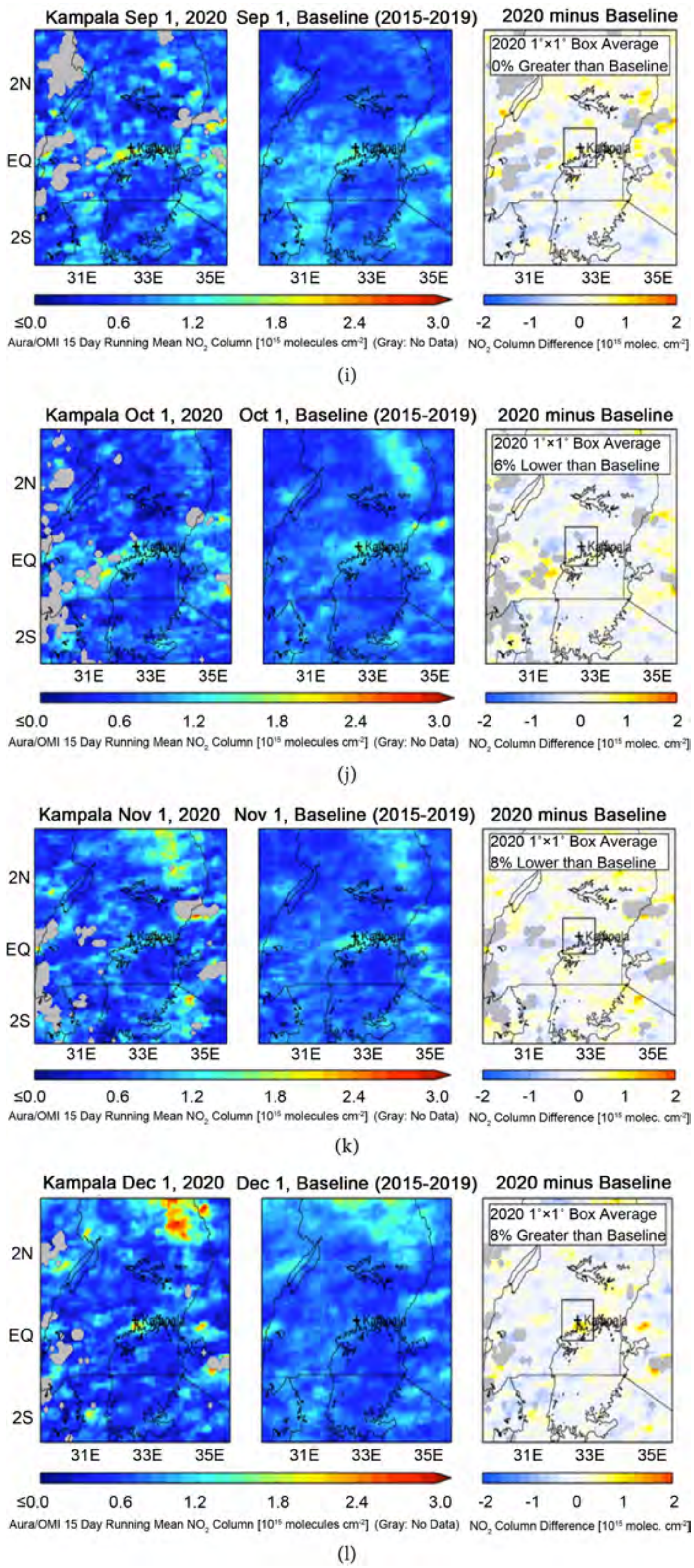
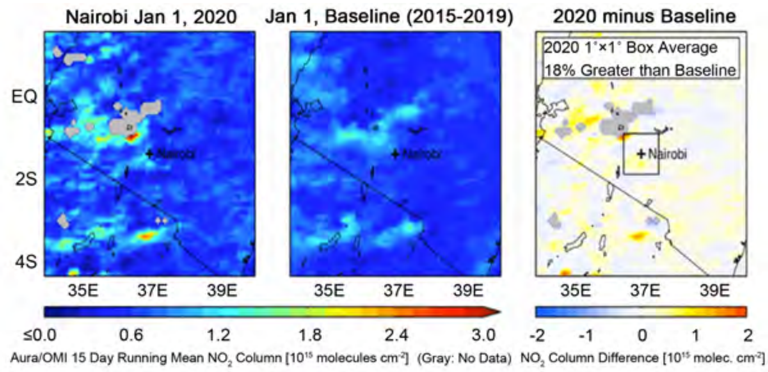
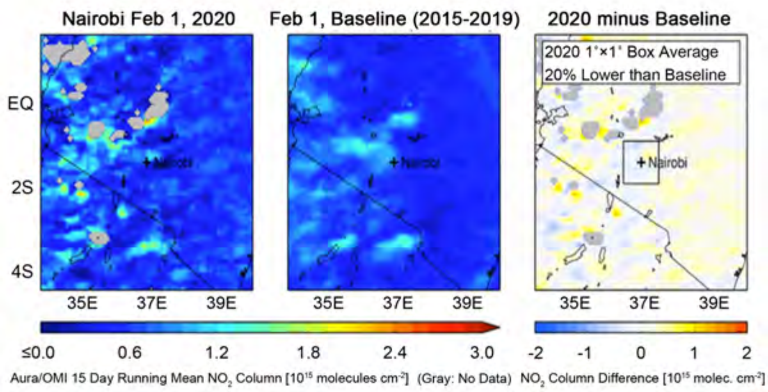


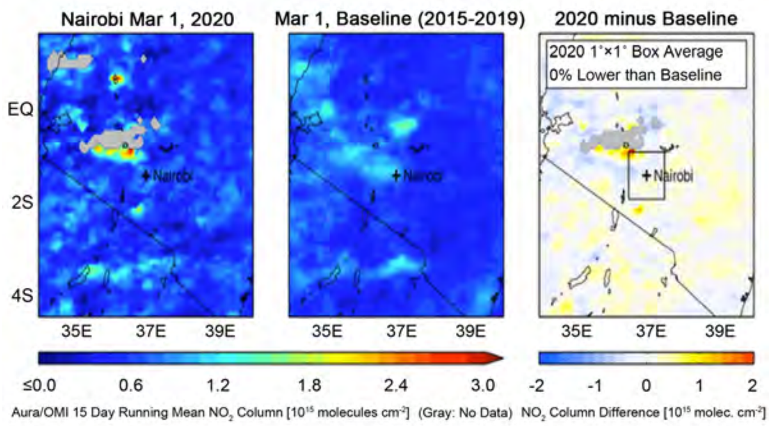
Figure 2. Tropospheric NO_2 emissions over Kampala, Uganda (32.58E, 0.35N) for 2020 and the baseline (2015-2019). Results are for 1˚ Latitude × 1˚ Longitude box around city center.


Nairobi Jan 1, 2020
Jan 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
18% Greater than Baseline
EQ
2S
4S
35E 37E 39E
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

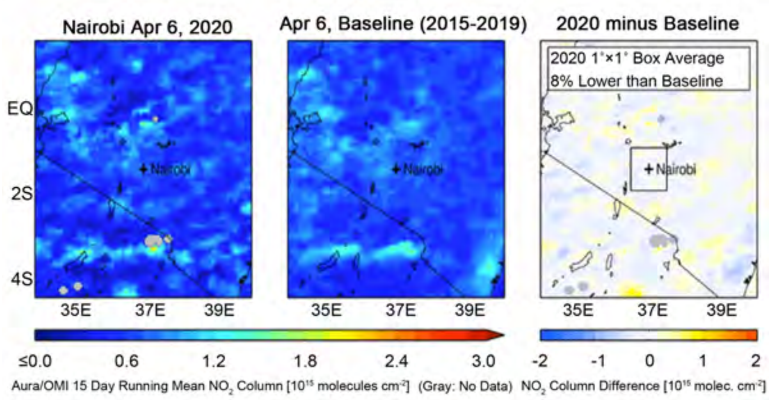
(a)


Nairobi Feb 1, 2020
Feb 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
20% Lower than Baseline
EQ
2S
4S
35E 37E 39E
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

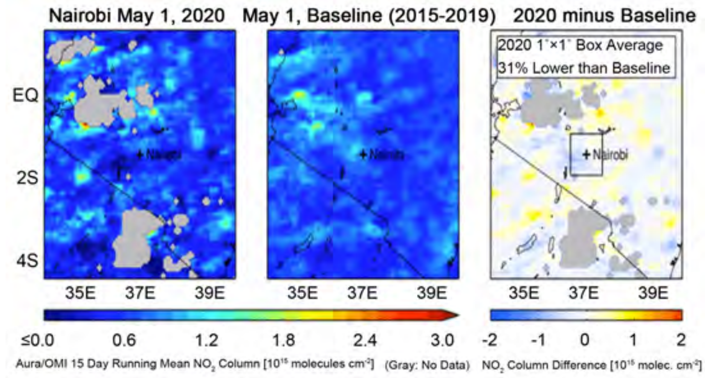
(b)

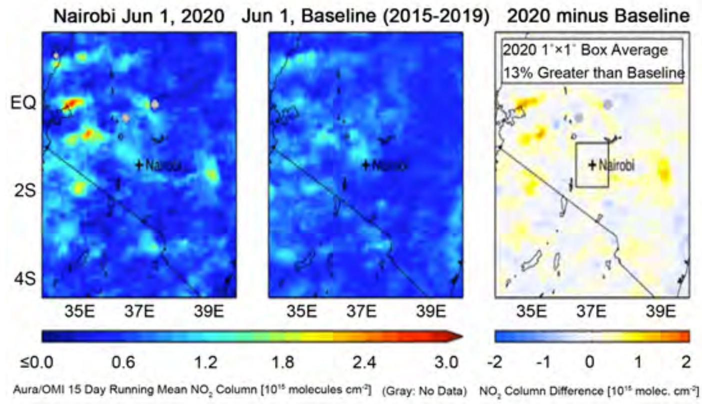

Nairobi Mar 1, 2020
Mar 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
0% Lower than Baseline
EQ
2S
4S
35E 37E 39E
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

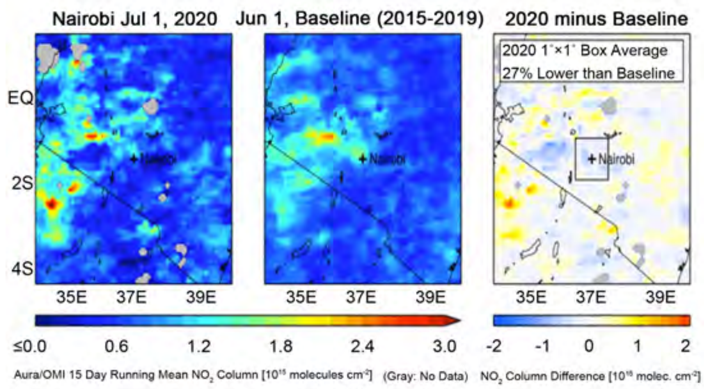
(c)

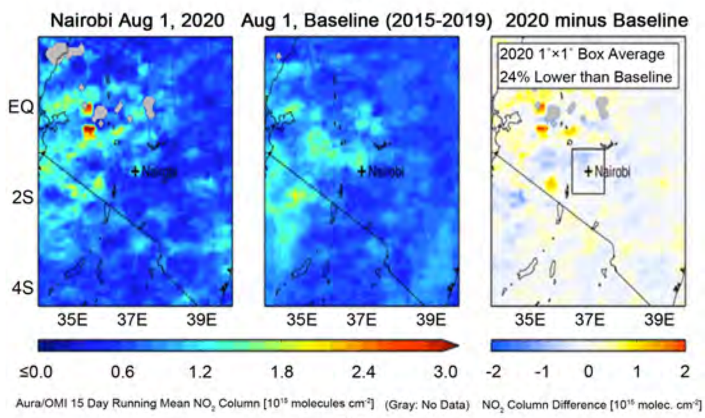

Nairobi Apr 6, 2020
Apr 6, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
8% Lower than Baseline
EQ
2S
4S
35E 37E 39E
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

(d)


Nairobi May 1, 2020
May 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
31% Lower than Baseline
EQ
2S
4S
35E 37E 39E
35E 37E 39E
35E 37E 39E
Nairobi
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]
(e)


Nairobi Jun 1, 2020
Jun 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
13% Greater than Baseline
EQ
2S
4S
35E 37E 39E
35E 37E 39E
35E 37E 39E
Nairobi
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]
(f)


Nairobi Jul 1, 2020
Jun 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
27% Lower than Baseline
EQ
2S
4S
35E 37E 39E
35E 37E 39E
35E 37E 39E
Nairobi
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]
(g)


Nairobi Aug 1, 2020
Aug 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
24% Lower than Baseline
EQ
2S
4S
35E 37E 39E
35E 37E 39E
35E 37E 39E
Nairobi
≤0.0 0.6 1.2 1.8 2.4 3.0
-2 -1 0 1 2
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]
(h)

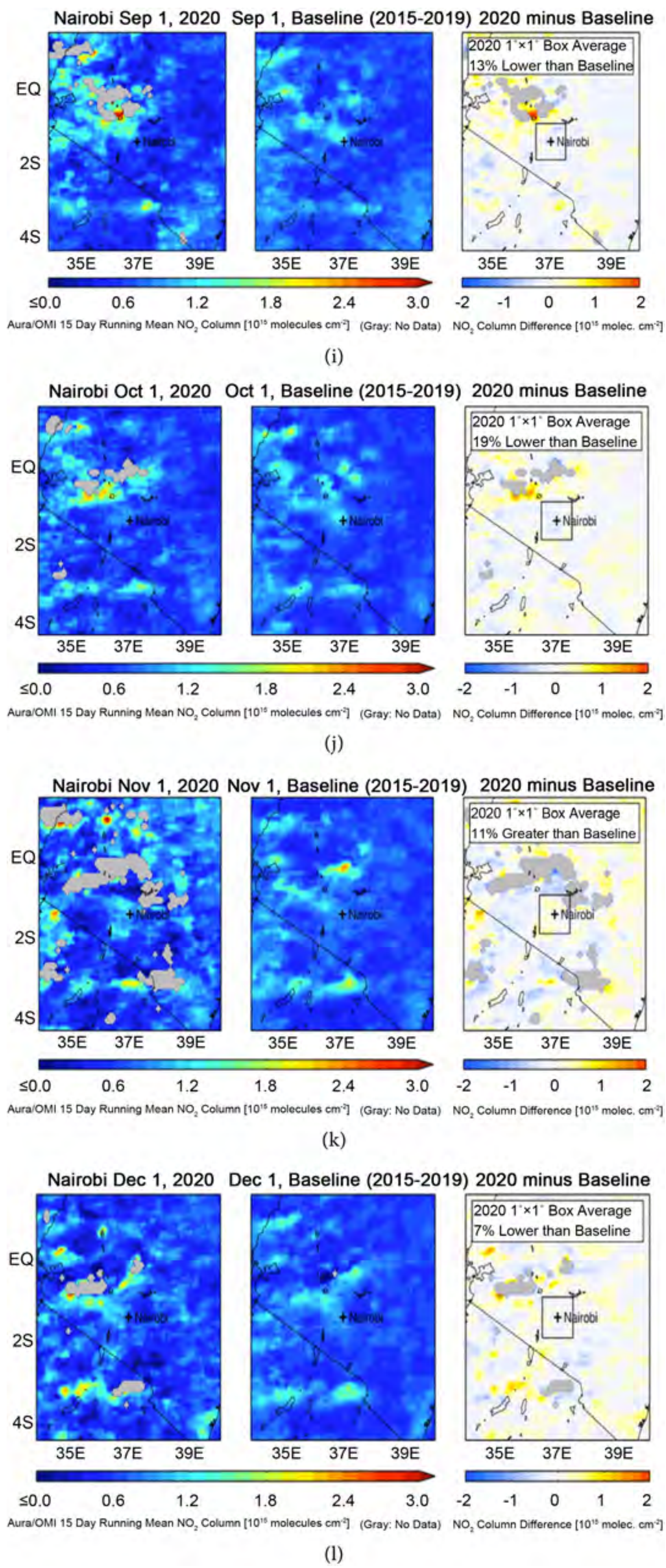
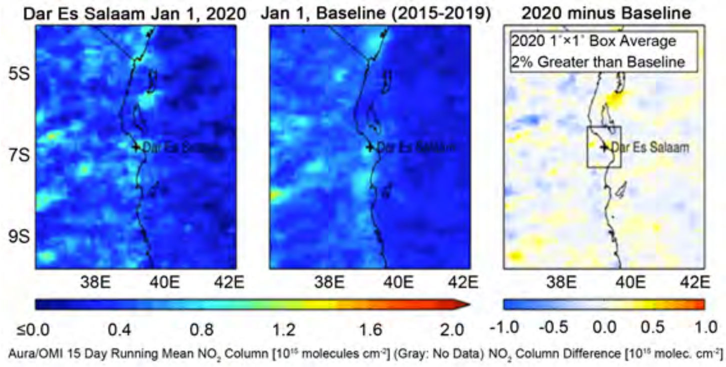
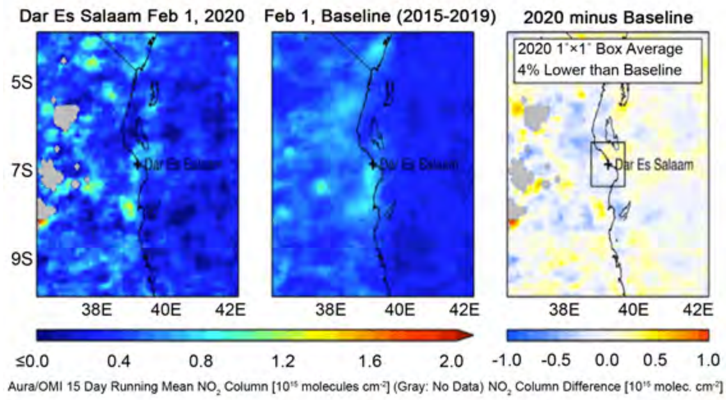


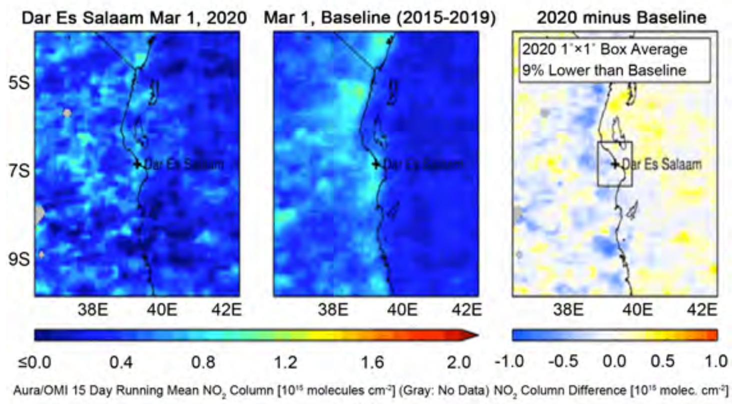
Figure 3. Tropospheric NO_2 emissions over Nairobi, Kenya (36.29E, 1.42S) for 2020 and the baseline (2015-2019). Results are for 1˚ Latitude × 1˚ Longitude box around city center.


Dar Es Salaam Jan 1, 2020
Jan 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
2% Greater than Baseline
5S
7S
9S
38E
40E
42E
Dar Es Salaam
≤0.0
0.4
0.8
1.2
1.6
2.0
-1.0
-0.5
0.0
0.5
1.0
Aura/OMI 15 Day Running Mean NO₂ Column [10¹⁵ molecules cm⁻²] (Gray: No Data)
NO₂ Column Difference [10¹⁵ molec. cm⁻²]

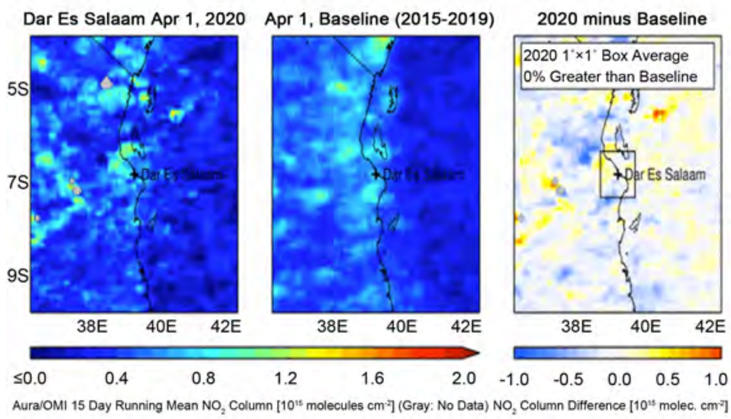
(a)


Dar Es Salaam Feb 1, 2020
Feb 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
4% Lower than Baseline
5S
7S
9S
38E
40E
42E
Dar Es Salaam
≤0.0
0.4
0.8
1.2
1.6
2.0
-1.0
-0.5
0.0
0.5
1.0
Aura/OMI 15 Day Running Mean NO₂ Column [10¹⁵ molecules cm⁻²] (Gray: No Data)
NO₂ Column Difference [10¹⁵ molec. cm⁻²]

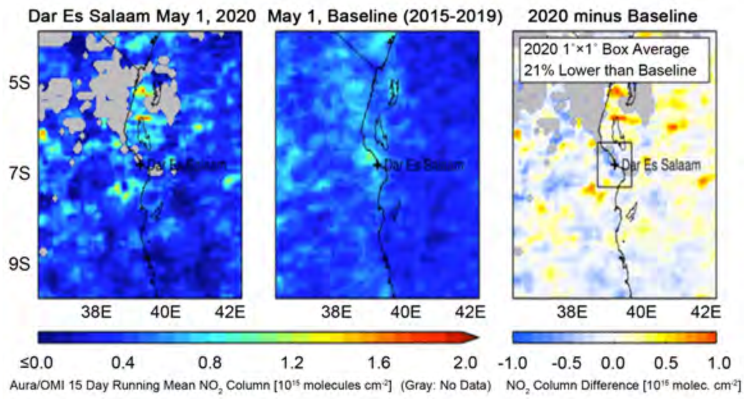
(b)


Dar Es Salaam Mar 1, 2020
Mar 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
9% Lower than Baseline
5S
7S
9S
38E
40E
42E
Dar Es Salaam
≤0.0
0.4
0.8
1.2
1.6
2.0
-1.0
-0.5
0.0
0.5
1.0
Aura/OMI 15 Day Running Mean NO₂ Column [10¹⁵ molecules cm⁻²] (Gray: No Data)
NO₂ Column Difference [10¹⁵ molec. cm⁻²]

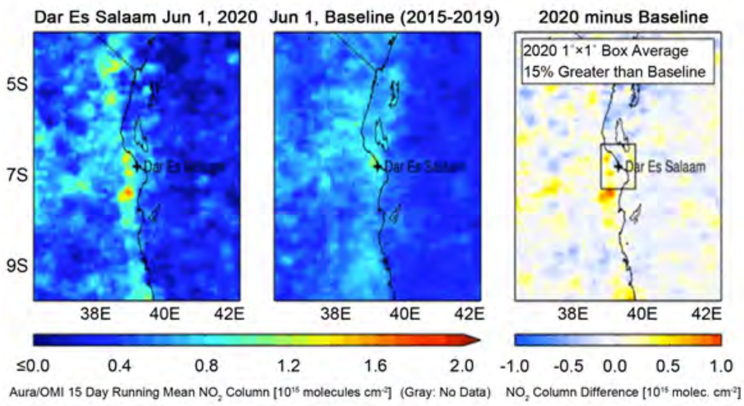
(c)


Dar Es Salaam Apr 1, 2020
Apr 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
0% Greater than Baseline
5S
7S
9S
38E
40E
42E
Dar Es Salaam
≤0.0
0.4
0.8
1.2
1.6
2.0
-1.0
-0.5
0.0
0.5
1.0
Aura/OMI 15 Day Running Mean NO₂ Column [10¹⁵ molecules cm⁻²] (Gray: No Data)
NO₂ Column Difference [10¹⁵ molec. cm⁻²]

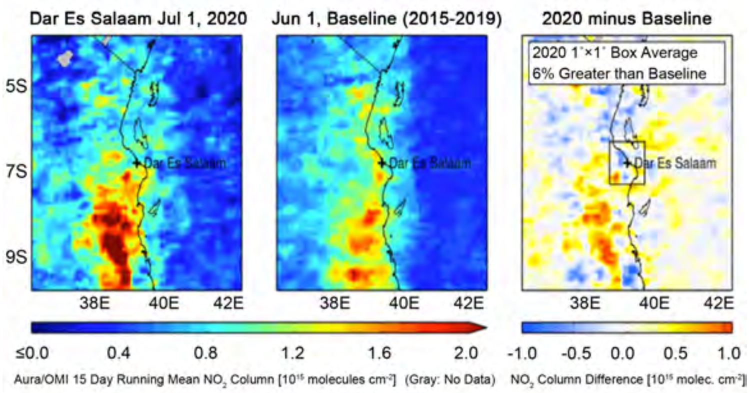
(d)


Dar Es Salaam May 1, 2020
May 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
21% Lower than Baseline
5S
7S
9S
38E 40E 42E
Dar Es Salaam
≤0.0 0.4 0.8 1.2 1.6 2.0
-1.0 -0.5 0.0 0.5 1.0
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

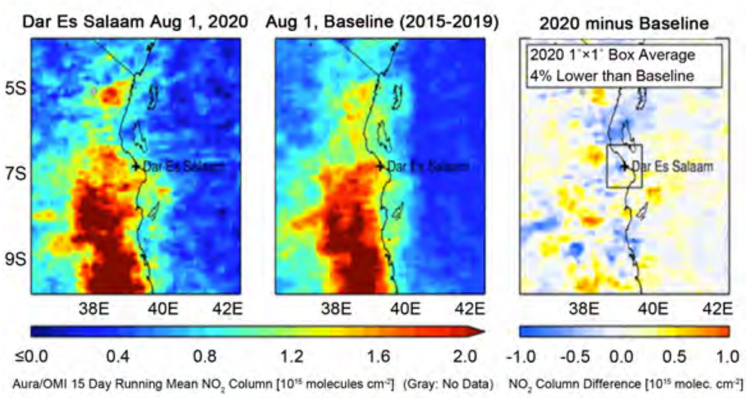
(e)


Dar Es Salaam Jun 1, 2020
Jun 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
15% Greater than Baseline
5S
7S
9S
38E 40E 42E
Dar Es Salaam
≤0.0 0.4 0.8 1.2 1.6 2.0
-1.0 -0.5 0.0 0.5 1.0
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

(f)


Dar Es Salaam Jul 1, 2020
Jun 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
6% Greater than Baseline
5S
7S
9S
38E 40E 42E
Dar Es Salaam
≤0.0 0.4 0.8 1.2 1.6 2.0
-1.0 -0.5 0.0 0.5 1.0
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

(g)


Dar Es Salaam Aug 1, 2020
Aug 1, Baseline (2015-2019)
2020 minus Baseline
2020 1°×1° Box Average
4% Lower than Baseline
5S
7S
9S
38E 40E 42E
Dar Es Salaam
≤0.0 0.4 0.8 1.2 1.6 2.0
-1.0 -0.5 0.0 0.5 1.0
Aura/OMI 15 Day Running Mean NO2 Column [10^15 molecules cm^-2] (Gray: No Data)
NO2 Column Difference [10^15 molec. cm^-2]

(h)

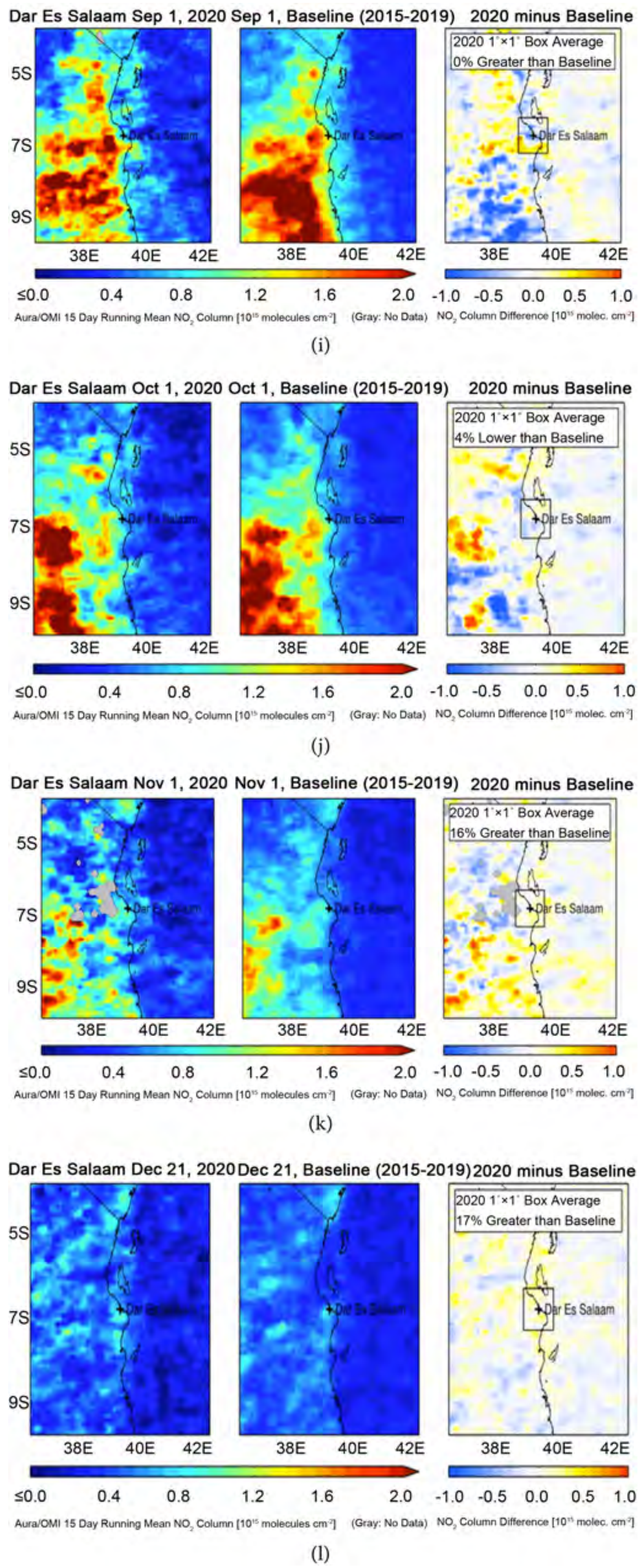


Figure 4. Tropospheric NO_2 emissions over Dar es Salaam, Tanzania (39.25E, 6.80S) for 2020 and the baseline (2015-2019). Results are for 1˚ Latitude × 1˚ Longitude box around city center.

February. This could be due to reduced industrial production post-festive season of 2019. On March 1st 2020, there was no net increase in NO_2 emissions when compared to 2015-2019 baseline. On 6th April 2020 when a partial lockdown was considered, NO_2 emissions were 8% lower than the baseline. This could have been due to decreased industrial production and vehicular movements. For May, July, August, September, October, November and December, NO_2 emissions in Nairobi were 31%, 27%, 24%, 13%, 19%, 11% and 7% lower than the baseline. On 1st June 2020, NO_2 emissions were 13% greater than the baseline. The lower reductions in percentage emissions of NO_2 from May to December 2020 could be due to the gradual easing of COVID-19 restrictions by the government, including allowing resumption of work, industrial activities and public transport *i.e.* vehicular movements [25]. Within Nairobi metropolitan area for example, movement restrictions in the Eastleigh area were lifted [26]. The November-December lower percentage reductions in NO_2 emissions could also be explained by increased industrial production and vehicular movements ahead of the festive season (Christmas celebrations on 25th December 2020 and the new year celebration of 1st January 2021).

Interestingly, the observed reductions in NO_2 emissions in 2020 over Kampala and Nairobi cities have not been the case with Tanzania where there was no lockdown instituted. As seen in **Figure 4(a)**, Dar es Salaam had 4% greater NO_2 emissions than the baseline on January 1st 2020 which reduced to 4% lower than the baseline in February 2020 (**Figure 4(b)**). In March when COVID-19 became a reality in the EAC, NO_2 emissions dropped by 9% lower than the baseline (**Figure 4(c)**). This could be because the country initially tried to follow WHO guidelines in containing the virus and reduced vehicular traffic in its coastal city of Dar es Salaam [27] [28]. In April 2020, there was no net difference between the NO_2 emissions in the city as compared to the 2015-2019 baseline, but this increased to 21% lower than the baseline in May 2020. When the president declared the country "coronavirus-free" in June 2020 and allowed free movements and operation of industries [29] [30], NO_2 emissions increased by 15% and 4% greater than the baseline for June and July 2020 (**Figure 4(f)** and **Figure 4(g)**). After this, NO_2 emissions were 4% lower than baseline in August 2020. There was no net difference in NO_2 emissions over Dar es Salaam in September 2020 but this decreased to 4% lower than the baseline in October 2020. November 2020 and December 2020 recorded 16% and 17% increase in NO_2 emissions when compared to the baseline. This indicates that the lockdown containment measure could have had a reductive effect on NO_2 emissions in Dar es Salaam.

Overall, there were about 6.0% and 8.91% reductions in NO_2 emissions over Kampala and Nairobi in 2020 while Dar es Salaam had about 1.16% increase in NO_2 emissions. These findings are in agreement with the percentage reduction in the use of gasoline and diesel from March 2020 for Kampala and Nairobi. Thus, the reductions in NO_2 emissions could mainly be attributable to the reductions in vehicular traffic and industrial activities during the pandemic year

(2020). The NO_2 emissions reported were comparable to those retrieved from the Google community mobility reports based on anonymized datasets from users in Kampala and Nairobi cities [31] [32]. High air pollution levels in Tanzanian city of Dar es Salaam is not a new report; it had been reported by previous authors to be caused by its heavy traffic, especially in the rush hours [33] [34] [35].

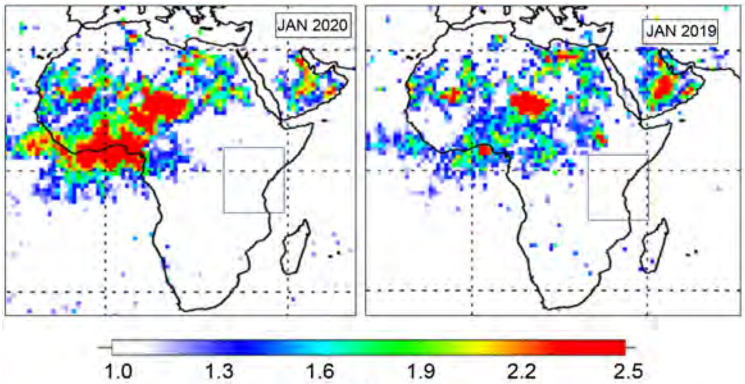
Reduction in NO_2 levels during the novel COVID-19 pandemic have been previously reported in other countries (cities) including China [17], Cairo and Alexandria governorates of Egypt [15], United States of America [1], India [36] [37], Kingdom of Saudi Arabia [38], Sao Paulo and Rio de Janeiro of Brazil [39] [40], Croatia [41], Barcelona of Spain [42], Southern European cities of Nice, Rome, Valencia and Turin [43] and Italian cities of Florence, Milan, Pisa and Lucca [44] [45].

The concentration of NO_2 in the atmosphere is primarily a function of the magnitude of nitrogen oxide (NO_x) emissions and weather factors such as sun angle, wind speed and temperature, though meteorological variations between years can cause column NO_2 differences of ~15% over monthly timescales [46]. It is clear that the implemented COVID-19 lockdowns (March to May) reduced NO_2 emissions over Kampala and Nairobi, and thus improved air quality [47]. However, these improvements are temporary and unsustainable, with deterioration of air quality anticipated to upsurge as the countries resuscitate their economies post-lockdown or in the post-pandemic period as earlier witnessed in China [48]. It is imperative that stricter laws are enacted in the crucible of the fight against the virus itself so as to protect the environment of the individual countries, and the EAC at large.

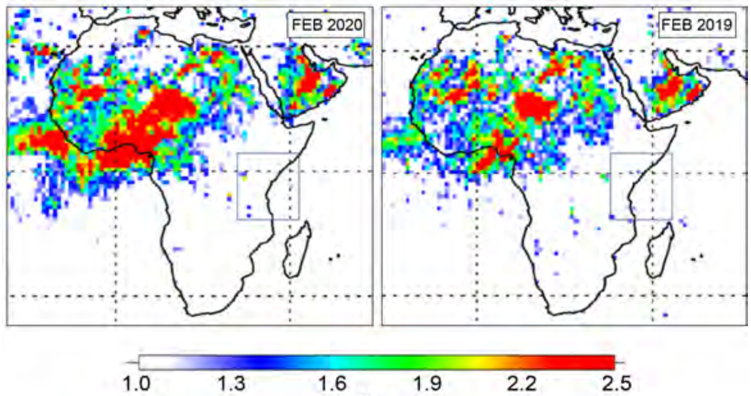
3.2. Changes in Absorbing Aerosol Index

As depicted in **Figure 5**, the 2020 absorbing aerosol index (AAI) in Kampala and Nairobi were lower than the AAI level during the same period in 2019 for February 2020 to May 2020 by about 1.91%, which confirms the positive effect of COVID-19 on air quality in Uganda and Kenya. In the other months, there were insignificant changes in AAI in Kampala and Nairobi. For Dar es Salaam, there were no appreciable increases in the AAI during the pandemic year. Recent reports indicate that much of the particulate matter emissions are from the transport sector (old private cars and taxis) from 6:00 am to 9:00 am in Kampala and the rest of Uganda [49], Nairobi [50] and Dar es Salaam [51]. This explains why lockdowns led to reduced AAI in the former than the latter. This is analogous to the situation reported previously in Egypt [52] [53].

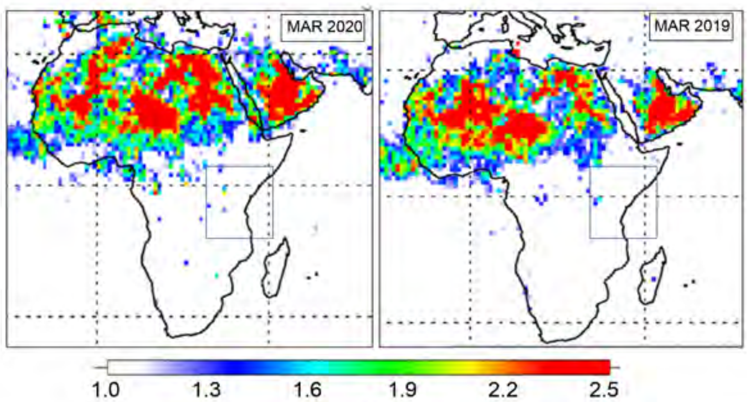
The stringent containment measures adopted by Uganda and Kenyan governments led to less traffic flow and relatively fewer construction activities. Less traffic flow usually leads to less particulate matter (PM) emissions from automobile engines particularly from old taxis and public transportation buses, tyre and brake wears and unmaintained roads [15] [50] [54]. Previous authors reported similar attenuation in PM levels during the COVID-19 in countries (cities) of


JAN 2020
JAN 2019
1.0
1.3
1.6
1.9
2.2
2.5

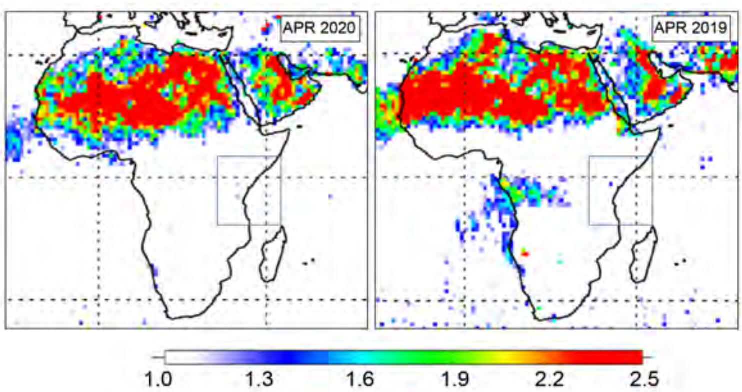
(a)


FEB 2020
FEB 2019
1.0
1.3
1.6
1.9
2.2
2.5

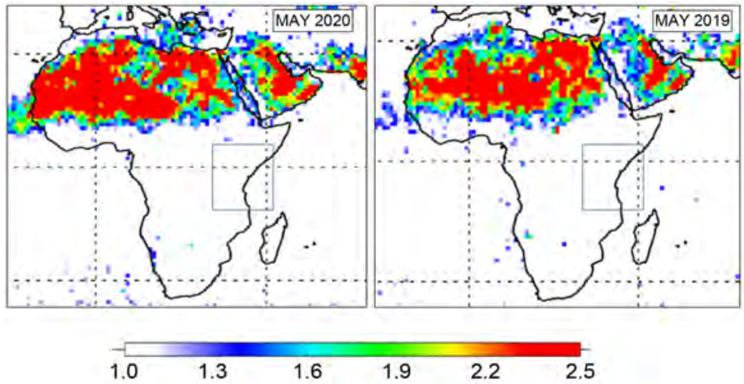
(b)


MAR 2020
MAR 2019
1.0
1.3
1.6
1.9
2.2
2.5

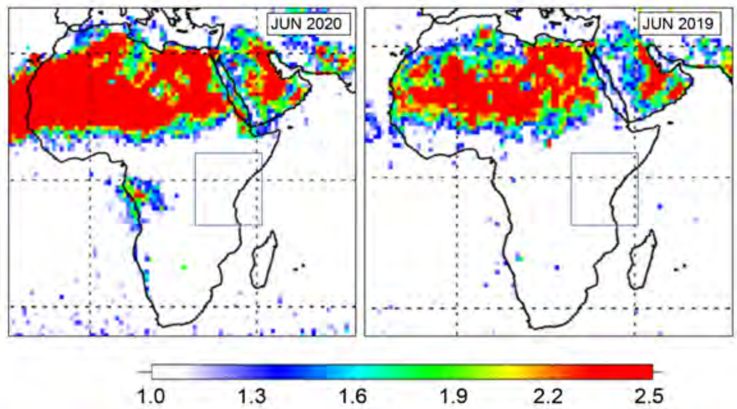
(c)


APR 2020
APR 2019
1.0
1.3
1.6
1.9
2.2
2.5

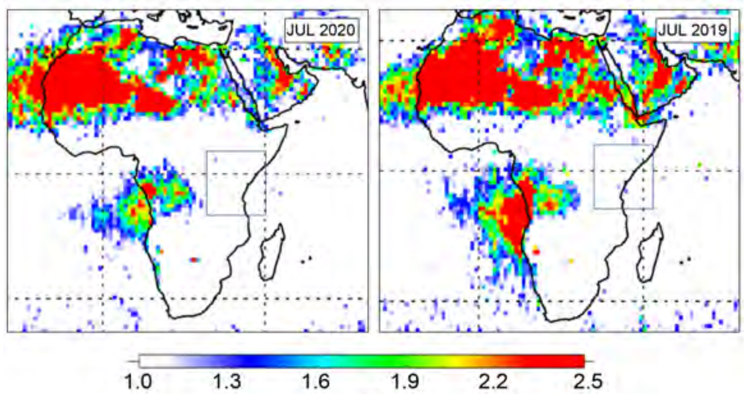
(d)


MAY 2020
MAY 2019
1.0 1.3 1.6 1.9 2.2 2.5

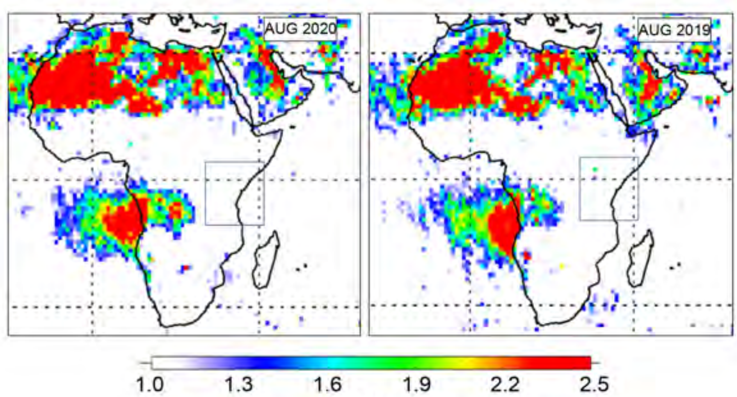
(e)


JUN 2020
JUN 2019
1.0 1.3 1.6 1.9 2.2 2.5

(f)


JUL 2020
JUL 2019
1.0 1.3 1.6 1.9 2.2 2.5

(g)


AUG 2020
AUG 2019
1.0 1.3 1.6 1.9 2.2 2.5

(h)

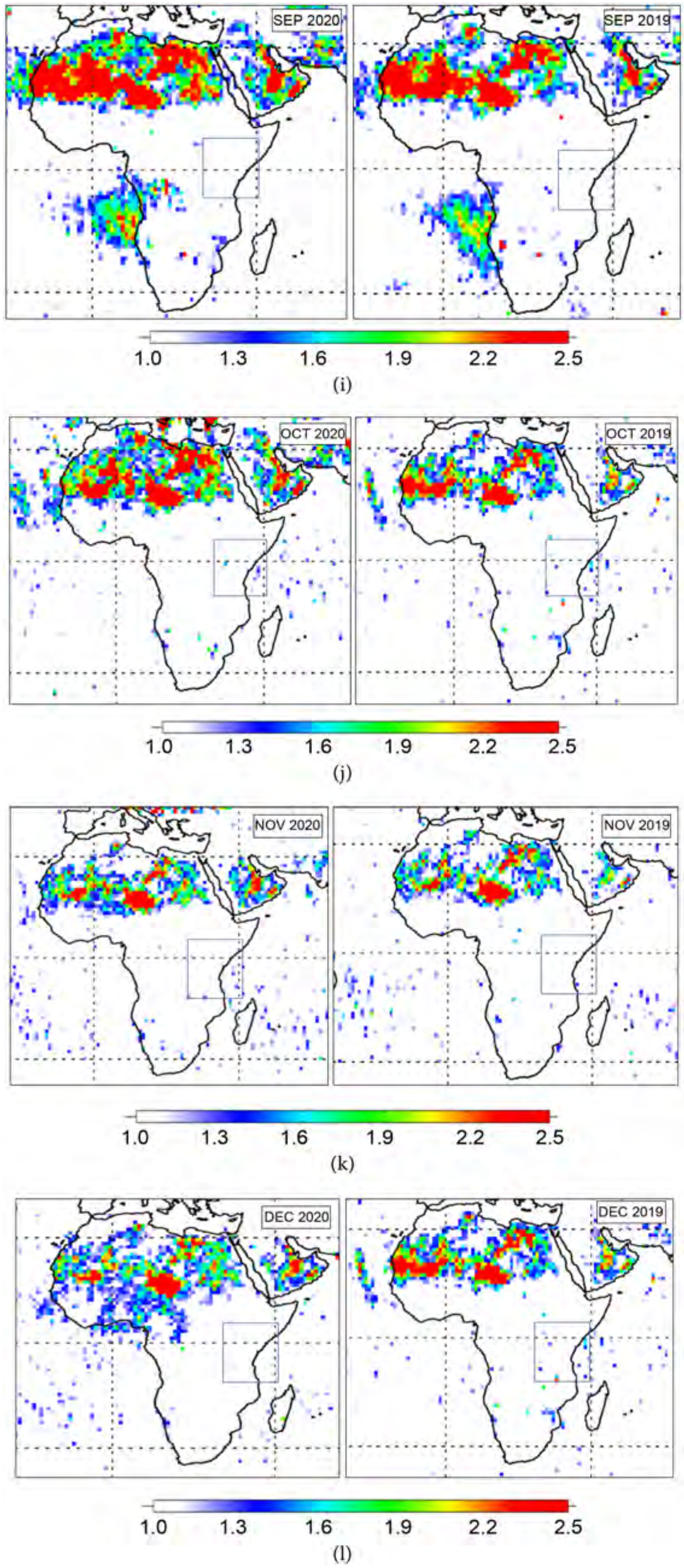


Figure 5. OMI/AURA Africa's Absorbing Aerosol Index for the year 2020 and baseline (2019). East Africa is focused with the square box.

Egypt [15], Rio de Janeiro and Sao Paulo, Brazil [39] [40], China [17] [55], India [37], Milan [45], Barcelona [42], Nice, Rome, Valencia and Turin [43]. The PM emissions in Kampala, Nairobi and Dar es Salaam has increasingly surpassed WHO regulatory guidelines in both PM_{10} and $PM_{2.5}$ size ranges [20] [34] [35] [47] [56]-[64]. Thus, there is need to tighten the air quality guidelines to maintain the air quality levels.

4. Conclusion

COVID-19 has been a crisis that has led to the undermining of environmental priorities and the realization of some Sustainable Development Goals. It has been visualized as a prelude to a looming future climate crisis, yet reports have also indicated that lockdowns imposed as a COVID-19 containment measure worldwide have led to improvement in air quality in various regions. The paucity of published reports or systematic and regulatory grade measurements of air pollution in East African cities prompted the current study. The results indicated that the imposed lockdowns in Kampala and Nairobi cities led to reductions in NO_2 emissions by 6.0% and 8.91%, while the AAI decreased by about 1.91% for the year 2020. Dar es Salaam recorded a 1.16% increase in NO_2 emissions though the AAI remained almost constant in 2020. The interim pollution reduction witnessed during the COVID-19 lockdown in Uganda and Kenya indicates that the region needs stimulus packages that prioritize low-carbon approaches in the post-pandemic era, with a shift to both clean and renewable energy. We recommend the installation of continuous air pollution monitoring centers within the region so as to provide data for evidentiary comparison of air pollution levels.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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