GeoHealth

RESEARCH ARTICLE

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Special Section:
The COVID-19 pandemic and environmental conditions in Africa

Key Points:

- Surges COVID-19 cases occurred during the wet and dry seasons of 2020 in West Africa
- The highest correlations are between Weekly new COVID-19 Cases and $PM_{2.5}$ are found in Nigeria during the dry season of 2020–2021
- New COVID-19 cases are decoupled from wet and dry seasons in Cabo Verde and the first wave in Angola lags biomass burning by several months

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

G. S. Jenkins,
gsj1@psu.edu

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Author Contributions:

Conceptualization: E. N. Toure
Data curation: S. M. Freire, T. Ogunro, D. Niang, M. Andrade, M. S. Drame, J. B. Huvi, E. E. S. Pires, M. Camara
Investigation: S. M. Freire

COVID-19 New Cases and Environmental Factors During Wet and Dry Seasons in West and Southern Africa

G. S. Jenkins[1], S. M. Freire[2], T. Ogunro[3], D. Niang[4], M. Andrade[2], M. S. Drame[4], J. B. Huvi[5], E. E. S. Pires[6], E. N. Toure[7], and M. Camara[8]

[1]Alliance for Education, Science, Engineering and Design with Africa (AESEDA), Pennsylvania State University, University Park, PA, USA, [2]University of Cabo Verde, Praia, Cape Verde, [3]Lead City University, Ibadan, Nigeria, [4]Cheikh Anta Diop University, Dakar, Senegal, [5]Instituto Superior de Ciências da Educação de Benguela - Angola, Benguela, Angola, [6]Centro de Estudos e Pesquisa do Tundavala, Engineering Department, ISPTundavala, Lubango, Angola, [7]University Felix Houphouet Biogny, Abidjan, Cote D'Ivorie, [8]University of Assane Seck, Ziguinchor, Senegal

Abstract Sub-Saharan Africa has been the last continent to experience a significant number of cases in the novel Coronavirus (COVID-19). Studies suggest that air pollution is related to COVID-19 mortality; poor air quality has been linked to cardiovascular, cerebrovascular, and respiratory diseases, which are considered co-morbidities linked to COVID-19 deaths. We examine potential connections between country-wide COVID-19 cases and environmental conditions in Senegal, Cabo Verde, Nigeria, Cote D'Ivorie, and Angola. We analyze $PM_{2.5}$ concentrations, temperatures from cost-effective in situ measurements, aerosol optical depth (AOD), and fire count and NO_2 column values from space-borne platforms from 1 January 2020 through 31 March 2021. Our results show that the first COVID-19 wave in West Africa began during the wet season of 2020, followed by a second during the dry season of 2020. In Angola, the first wave starts during the biomass burning season but does not peak until November of 2020. Overall $PM_{2.5}$ concentrations are the highest in Ibadan, Nigeria, and coincided with the second wave of COVID-19 in late 2021 and early 2022. The COVID-19 waves in Cabo Verde are not in phase with those in Senegal, Nigeria, and Cote, lagging by several months in general. Overall, the highest correlations occurred between weekly new COVID-19 cases meteorological and air quality variables occurred in the dry season.

Plain Language Summary The link between environmental conditions, COVID-19 severity, and mortality has been examined in the global north; however, limited studies have examined the connections in Africa. We explore the linkage between COVID-19 cases and environmental conditions in Angola, Cabo Verde, Cote D'Ivorie, Nigeria, and Senegal during the first two COVID-19 waves of 2020 and early 2021. The first COVID-19 wave in Cote D'Ivorie, Nigeria, and Senegal occurred during the wet season of 2020 and during the dry season in Angola in 2020. The second wave occurs during the dry season in Cote D'Ivorie, Nigeria, and Senegal, with the poorest air quality occurring in concert with the COVID-19 wave in Nigeria. Southern parts of Nigeria also show elevated NO_2 column levels because of seasonal biomass burning, further reducing air quality.

1. Introduction

The novel coronavirus COVID-19, first detected in Wuhan, China, in December 2019, has become a global pandemic, with more than 60 million known cases and 1.5 million deaths worldwide as of 1 December 2020. COVID-19 deaths are linked to co-morbidities such as heart disease, diabetes, obesity, and respiratory disease, as well as exposure to higher concentrations of air pollution (Clerkin et al., 2020; Jordan et al., 2020; Wu et al., 2020). The largest number of cases have occurred in North America, Europe, and Asia in countries such as the United States, Spain, Italy, India, and Brazil. In the United States, racial differences in COVID-19 mortality have been found in African Americans and other minority groups (Chang et al., 2020; Tai et al., 2020; Yancy, 2020). These higher mortality rates among African Americans are related to higher rates of co-morbidities and other socio-economic disparities relative to other racial groups. Coincidentally, African Americans are subject to the highest burden of emissions from air pollution sources, and older African Americans have the highest mortality rates due to pollution in the United States (Di et al., 2017; Mikati et al., 2018). Older patients who have contracted COVID-19 also have a higher chance of dying in nursing home facilities (O'Driscoll et al., 2020).

Methodology: D. Niang, J. B. Huvi, E. E. S. Pires
Validation: S. M. Freire, T. Ogunro, M. Andrade, E. N. Toure
Writing – original draft: S. M. Freire, E. N. Toure
Writing – review & editing: S. M. Freire, T. Ogunro, D. Niang, M. Andrade, M. S. Drame, J. B. Huvi, E. E. S. Pires, M. Camara

Surprisingly, Africa has been the last continent to see a surge in COVID-19 cases, with South Africa having nearly 750,000 cases as of 1 December 2020, followed by Ethiopia. Salyer et al. (2021) report that only 3.4% of the cases were found in Africa, with 43% of these cases found in Southern Africa as of 31 December 2020. However, the case fatality rate (CFR) is higher in several African countries relative to the global CFR of 2.2%, with a CFR of 6.6% in Chad as of 31 December 2020. Governments in Africa undertook public health and social measures (PHSM) before the first cases were reported (Salyer et al., 2021).

Even though COVID-19 cases in Africa are lower than those in high and middle-income countries, there are reasons for concern, including the lack of critical health facilities and equipment such as intensive care units, ventilators, and health care staff (Wadvalla 2020). Sub-Saharan Africa's young population may provide a partial answer to the lower number of fatalities in many countries, given the propensity of COVID-19 to lead to greater fatalities in older people, but it does not fully explain why so few have contracted the virus in Africa. Mbow et al. (2020) suggest that the age differences should lead to four times less the number of COVID-19 cases instead of a factor of 40 and suggest that other factors related to the immune system may be at work. Because of the limited COVID-19 tests, the expense of tests for low-income populations, and the potential focus of testing at borders and airports in Sub-Saharan Africa, there is a strong possibility that the numbers of COVID-19 cases are underreported. Salyer et al. (2021) point out the greatest number of tests in Sub-Saharan Africa occurred in Southern Africa, with approximately 48,450 tests per million persons. In December 2021, West Africa had a test ratio of 9,278 per million persons as of December 2021. Bonnet et al. (2021) analyzed the COVID-19 pandemic in francophone West Africa, showing high attack rates of 94.75 per 100,000, and temporal-spatial analyses showed that the various COVID-19 waves occurred at different locations in Burkina Faso and Senegal, and not necessarily in urban centers.

Recently, serotyping of blood in Africa has provided potential insights into the number of people that may have been infected with COVID-19. Lewis et al. (2022) undertook a systematic review of seroprevalence studies in Africa. They find that COVID-19 seroprevalence rose from l3% to 65% by the third quarter of 2021. The rise occurred in 2021 when several variants were found in Africa. Lewis et al. (2022) do not find any significant difference in seroprevalence except in the 0–9 age group. Furthermore, the ratio of seroprevalence to cumulative incidence is substantial in Africa. They suggest that instead of the 8.2 million confirmed cases in Africa, there were an estimated 800 million COVID-19 infections.

The environment may also play a direct or indirect factor in the spread or seriousness of COVID-19 cases. Atmospheric pollutants such as NO_2 and $PM_{2.5}$ aerosols caused by urbanization, traffic, and industrial sources are associated with higher incidence and mortality rates of respiratory diseases leading to an estimated nine million premature deaths worldwide (Landrigan et al., 2018). Because COVID-19 is a viral respiratory disease that is considered to be highly contagious, it is possible that aerosols can serve as a transport mechanism for spreading the disease (Milicevic et al., 2021). Studies have linked atmospheric pollutants such as NO_2 and $PM_{2.5}$ to COVID-19 cases and mortality in the United States, Europe, and China (Copat et al., 2020; Frontera et al., 2020; Liang et al., 2020; Ogen, 2020; Wu et al., 2020; Yongjian et al., 2020). The linkage between temperature, and COVID cases remains unclear, with cold temperatures being expected to increase COVID-19 cases and warmer temperatures potentially reducing COVID-19, but early results show regional variations (Chien & Chen, 2020; Choi et al., 2021; Ma et al., 2021; Prata et al., 2020; Sarkodie & Owusu, 2020). Adekunle et al. (2020) found that temperature and relative humidity were negatively correlated to confirmed COVID-19 cases. Shao et al. (2022) found that temperatures were negatively correlated to COVID-19 mortality on the other hand, Sasikumar et al. (2020) found increasing COVID-19 cases during very warm conditions. Diouf et al. (2021) show that temperatures and new COVID-19 cases in the Sahelian zone were positively correlated to temperature during the first wave but negatively correlated in Maghreb (Northern Africa) and Guinea regions. They also found a positive correlation between COVID-19 new cases and water vapor in the Sahelian and Guinea regions but negatively correlated in the Maghreb zone during the first wave. Sera et al. (2021) found no association between the reproduction number and atmospheric variables but suggest that government actions and behavior had a larger influence across 26 countries.

Elevated particulate matter (PM) and NO_2 levels pose the greatest threats to COVID-19 seriousness, as some COVID-19 variants and poor air quality impact the lower respiratory tract (Arora et al., 2021), when cardiovascular and respiratory diseases are present. PM sources in West and Southern Africa vary spatially and temporally due to numerous emission sources from urban pollution (Amegah & Agyei-Mensah, 2017; Petkova et al., 2013) to the Sahara Desert, which is the largest source of dust emissions globally (Engelstaedter et al., 2006). PM from biomass burning, deserts, and urban zones may drive infant mortality while also leading to premature death in Africa (Heft-Neal et al., 2018; Bauer et al., 2019). Air quality is poorly observed across all of Africa, but limited observations in West Africa show that hazardous particulate matter concentrations are frequently observed across the Sahelian regions, including the densely populated city of Dakar, Senegal (Diokhane et al., 2016; Marticorena et al., 2010; Toure et al., 2019).

The lack of real-time monitoring and measurements of particulate matter using in situ ground observations is the greatest obstacle to determining the relationship between air quality and COVID-19 in Sub-Saharan Africa. It also limits our fundamental understanding of air quality, cardiovascular and respiratory disease, in urban and rural areas. In this work, we use low-cost PM sensors (Ardon-Dryer et al., 2020; Bi et al., 2020) to observe air quality in West and Southern Africa during the COVID-19 pandemic. Using the PM sensor network in Nigeria, Ogunjo et al. (2022), found high $PM_{2.5}$ concentrations occurred during the second wave of COVID-19 across Nigeria.

The primary objective of this work is to examine trends in new weekly COVID-19 cases, meteorological and air quality variables in West Africa and Southern Africa in the five countries of Nigeria, Cote D'Ivorie, Senegal, Cabo Verde, and Angola from 1 January 2020 through 31 March 2021. In particular, we focus on satellite observations and limited in situ measurements of temperature and $PM_{2.5}$ concentrations using low-cost instruments.

2. Methodology and Data

We examine COVID-19 new cases and deaths with data from the World Health Organization (WHO) in Angola, Cabo Verde, Cote D'Ivorie, Nigeria, and Senegal (www.covid19.who.int). Daily COVID-19 new cases and deaths from each country are averaged over 1 week to account for countries that do not report each day. We examine rainfall, aerosol optical depth (AOD), column NO_2, fire counts through satellite sources, and the low-cost Purple Air (PA) and Clarity sensors to examine $PM_{2.5}$ concentrations and temperatures for environmental data. We estimate the population in each country from the United Nations middle standard for 2020 (United Nations, 2019). Because of the lack of surface air quality stations in Africa, there is a reliance on satellite data, hence, we focus on five countries where surface PM stations were in place during 2020–2021. Unfortunately, PM measurements were halted in Cote D'Ivorie in 2020 but we kept this country in our group and relied solely on satellite estimates for environmental variables. During the latter half of 2020 and early 2021, Nigeria increased its PM low-cost surface measurements which was used in Ogungo et al. (2022) to examine the relationship to COVID-19.

Daily $1° \times 1°$ gridded satellite-based AOD measurements are used based on the shapefile of each country from the Moderate Resolution Imaging Spectrometer (MODIS) instrument aboard the TERRA/AQUA using land and ocean point for Cabo Verde and the Deep Blue product for Angola, Cote D'Ivorie, Nigeria and Senegal (Hsu et al., 2013). The AOD data captures atmospheric aerosol loading from biomass burning, urban pollution, and mineral dust aerosols from Africa's deserts. Daily satellite AOD data is also averaged for 1 week for direct comparison to WHO COVID-19 new cases in each country, with missing data recorded and removed when cloud coverage is present.

Thermal anomalies from the VIIRS daily overpasses are used to identify fire locations in Angola, Cote D'Ivorie, Nigeria, and Senegal (Schroeder et al., 2014). Cabo Verde does not have a fire season, and not considered. Daily fire counts are averaged over 1 week for direct comparison to WHO COVID-19 new cases in each country. To examine the seasonal biomass burning and other anthropogenic trace gas emissions, we use column NO_2 to produce weekly values over the urban centers of Abidjan, Cote D'Ivorie; Lagos, Abuja and Kano, Nigeria; Dakar, Senegal; Kano, Nigeria; and Luanda, Angola, where column values are centered around each city (Lamsal et al., 2021). Daily $1° \times 1°$ gridded satellite-based precipitation using microwave, infrared, and the Global Precipitation Measurement (GPM) radar based on the shapefile of each country to estimate daily rainfall (Liu, 2016). Daily rainfall amounts are used to examine its relationship to weekly COVID-19 data and determine the start, middle, and end of the rainy periods.

Purple air (PA) devices are low-cost optical devices that provide high temporal resolution data (Ardon-Dryer, 2021; Bi et al., 2020; Ogunjo et al., 2022). The device includes two low-cost optical sensors used for determining particulate matter (PM_1, $PM_{2.5}$, and PM_{10}), relative humidity and temperature sensors, and sea level pressure. The data from each device was quality controlled with missing data taken into account and extreme outliers

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removed for each site. In some cases, especially for Angola, there is significant missing data and we use data for all available stations. We used daily and weekly averaged $PM_{2.5}$ concentrations and temperature data compared to country-wide COVID-19 new cases. We use the following stations for comparison to country-wide COVID-19 cases: Luanda, Angola (−8.929027°S 13.184946°E); Lobito, Angola (12.355968°S, 13.533997°E); Praia, Cabo Verde (14.911585°N, 23.526135°W); Ibadan, Nigeria (7.4430°N, 3.9036°E); Dakar, Senegal (14.681593°N −17.467438°W). The Clarity IO sensor is used for PM and temperature measurements at Lubango (−14.912945°S, 13.501719°E) (Kiser et al., 2021). Statistics are applied through Pearsons correlations, means, and statistical tests at $p < 0.1$ and $p < 0.05$.

3. Results

3.1. COVID-19 Statistics

Table S1 shows the total number of confirmed cases and deaths from 1 January 2020 through 31 March 2021 for the five countries. Nigeria produced the largest number of cases and fatalities, but the cases and deaths per capita were small because of its large population. Conversely, Cabo Verde had the smallest number of cases but had the largest number of cases and deaths per capita because of its small population (Salyer et al., 2021). Salyer et al. (2021) also show that Cabo Verde had the largest testing ratio (test per million) of the five countries, while Nigeria had the smallest ratio. A potential limitation of the reported COVID-19 tests is the availability and the cost of affordable tests across Sub-Saharan Africa versus COVID-19 tests, which were normally available at airports and possibly national borders for a cost.

Figure 1 shows the weekly number of COVID-19 cases and deaths for the five countries. Each of the countries experienced two waves from 2020 through the end of March 2021 but are not synchronous. The West African countries of Cote D' Ivorie, Nigeria, and Senegal experienced waves during the Northern Hemisphere (NH) summer of 2020 and winter seasons of 2020/2021. The second wave produced the largest number of cases overall; however, we find a larger number of deaths in Senegal for the second wave (∼700) relative to the first wave (∼300), suggesting greater severity in this wave (Figures 1a, 1c, and 1d). Cabo Verde experienced its first wave in the summer of 2020, followed by a second wave in November of 2020 and a third wave in March of 2021 (Figure 1b). The largest number of COVID-19-related deaths occurred during the second wave in November 2020. Angola showed increasing cases during the SH dry season (July 2020), which peaked in November of 2020 (Figure 1e). Smaller waves may have been present during January and March of 2021, but we will not consider them for analysis. The largest number of deaths in Angola occurred during the peak in November of 2020.

3.2. Precipitation Distribution and New COVID-19 Cases

Daily precipitation amounts and their relationship to COVID-19 weekly cases are shown in Figure 2. During the wet season of 2020, we observe the first COVID-19 wave in West Africa and Cabo Verde. During 2020, rainfall in West Africa and Cabo Verde (Figures 2a and 2b) occurs during the NH late spring and summer season (March–October), beginning the earliest (March) and ending the latest (November) in Nigeria and Cote D'Ivorie in 2020 (Figures 2c and 2d). The peak of the first COVID-19 wave occurs in the mature phases of the rainy season in Senegal, Cote D'Ivorie, and Nigeria (Figures 2a, 2c, and 2d). While the COVID-19 cases are increasing during the wet season in Cabo Verde, the daily rain amounts during 2020 were relatively small except for an extreme rainfall event during the first week in September (Figure 2b). Rainfall in Angola is out of phase with the Northern Hemisphere, with the wet season beginning during October and lasting through March. In 2020, Angola's wet season began before the COVID-19 pandemic. During the wet season in late 2020, the first COVID-19 wave declined, leading to a decrease in the number of weekly COVID-19 cases and deaths in Angola but increased slightly in early 2021 (Figure 2e). Accumulated weekly precipitation amounts are weakly correlated and not statistically significant at the 95% confidence level to new COVID-19 weekly cases during the wet season in Senegal, Cabo Verde, and Nigeria during the wet period (Table 1). Weekly Precipitation amounts and new COVID-19 cases are negatively correlated in Angola (Table 1).

3.3. Satellite Measures of Air Quality AOD, Fire Counts, Column NO_2 and New COVID-19 Cases

The dry season in West and Southern Africa is associated with an increased burden of aerosols from seasonal dust and biomass burning, which is likely to decrease air quality and increase adverse outcomes for respiratory

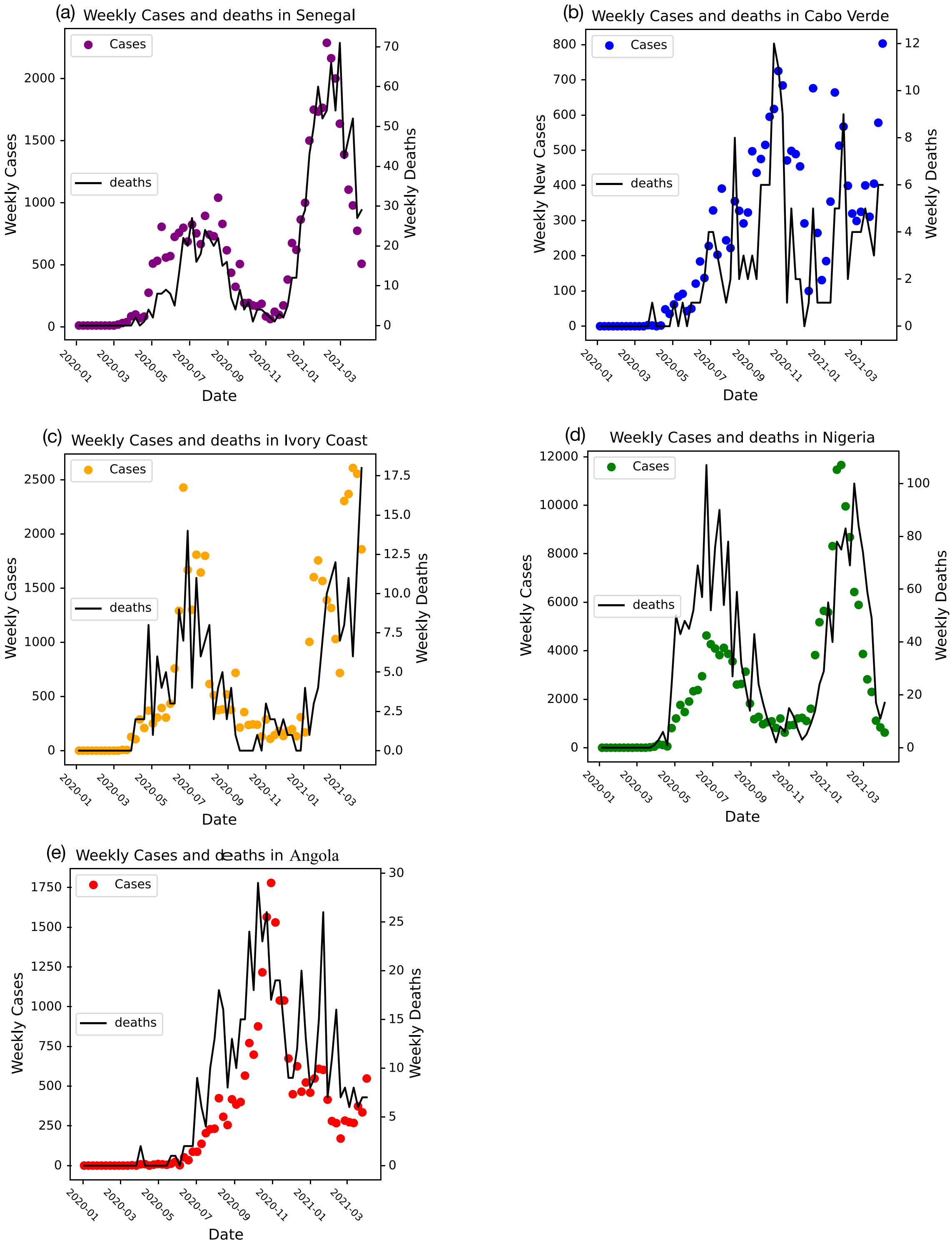

Figure 1. 1 January–31 March 2021 weekly confirmed new cases and deaths for: (a) Senegal; (b) Cabo Verde; (c) Cote D'Ivorie; (d) Nigeria, (e) Angola.

and cardiovascular disease. First, we examine column aerosol optical depth as a possible measure of air quality at the surface with the weekly AOD and new COVID-19 cases are shown in Figures 3a–3e. Higher AOD values are found during the first 3 months of 2020 in Cabo Verde and Senegal in response to Saharan dust transport and then during the late spring and early summer months with the establishment of the Saharan Air Layer (SAL) (Carlson & Prospero, 1972). Increasing AOD values are found from December 2020 through March 2021 in Senegal and

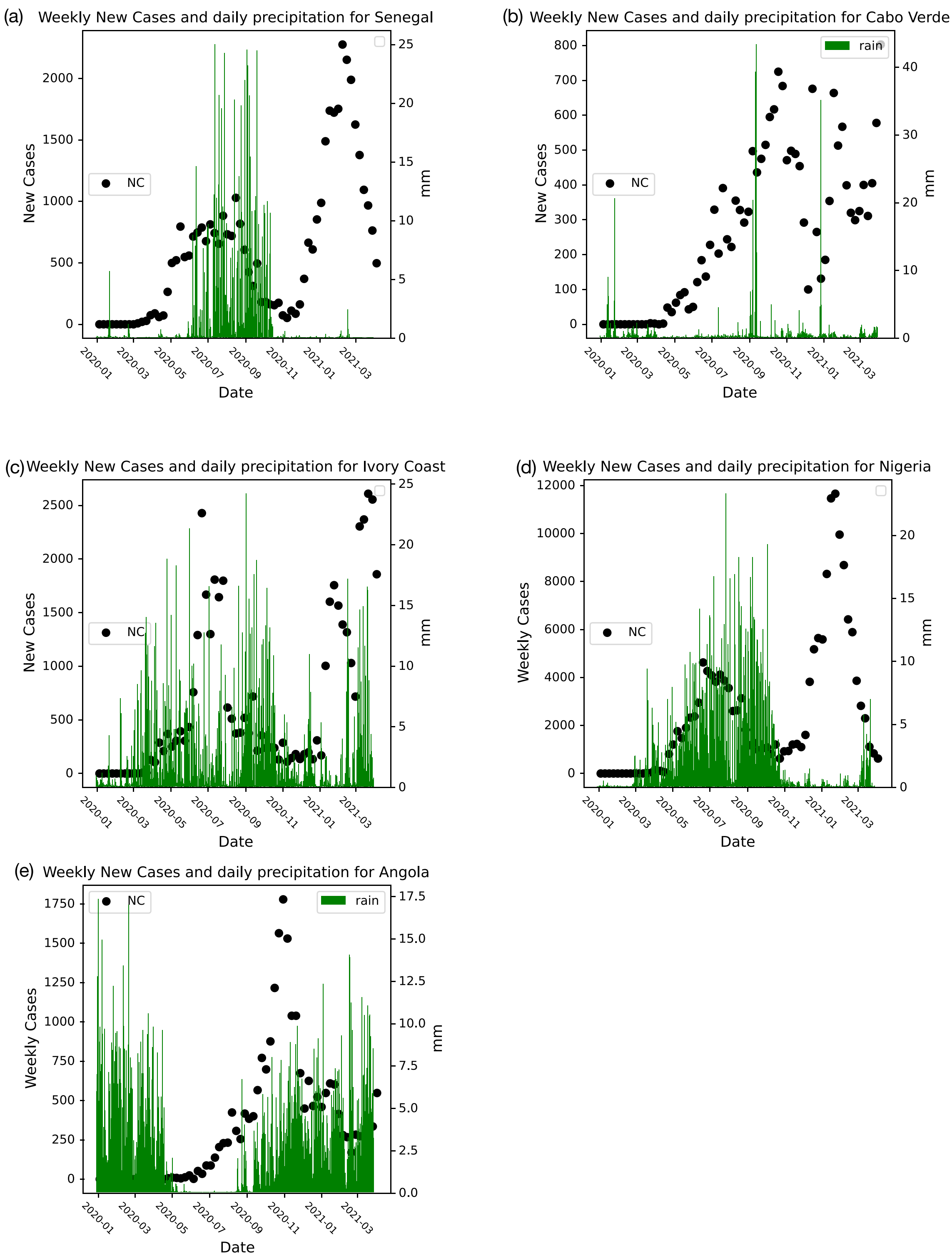

Figure 2. 1 January 2020–31 March 2021 weekly confirmed new cases and daily precipitation for: (a) Senegal; (b) Cabo Verde; (c) Cote D'Ivorie; (d) Nigeria, (e) Angola.

Cabo Verde. Increasing weekly COVID-19 cases occurred in May–June of 2020 and during the dry season of 2020 (November–December) when higher AOD values are observed (Figures 3a and 3b). Weekly countrywide AOD and new COVID-19 cases are weakly correlated except in Cabo Verde and Senegal during the first wave and second wave, respectively at the 95 and 90% confidence levels (Tables 1 and 2).

Table 1
Wave 1 Correlations Between New COVID-19 Cases and Atmospheric Variables (Correlation With New Cases)

	$PM_{2.5}$	Temp	Fire count	NO_2 column values	AOD	RHUM	Precip
Dakar, Senegal	−0.50*	0.44*	−0.42*	0.23	0.06	0.04	0.09
Praia CV	−0.29	0.03	n/a	n/a	−0.56*	−0.17	0.1
Ibadan Nigeria	0.28	−0.49*	−0.44*		0.09	0.44*	0.12
Lagos Nigeria	n/a	n/a	−0.44*	0.13	0.09	n/a	n/a
Abuja Nigeria	n/a	n/a	−0.44*	−0.40	0.09	n/a	n/a
Kano Nigeria	n/a	n/a	−0.44*	−0.05	0.09	n/a	n/a
Cote D'Ivorie	n/a	n/a	−0.38*	−0.31**	−0.06	n/a	−0.30
Luanda, Angola	−0.64*	−0.20	−0.80*	−0.80*	−0.04	−0.24	n/a
Liboto, Angola	−0.81*	0.54*	−0.80*	n/a	−0.04	0.13	n/a
Benguela, Angola	−0.15	0.33	−0.80*	n/a	−0.04	0.30	n/a
Lubango Angola	−0.3	0.33	−0.79*	n/a	−0.04	0.30	n/a

Note. Country wide satellite measurements are used for Fire count, NO_2. *$p < 0.05$, **$p < 0.10$.

In countries along the Gulf of Guinea, two distinct periods of higher AOD are found in Cote D'Ivorie and Nigeria (Figures 3c and 3d), beginning in January 2020 through April 2020. The AOD then begins to increase in late 2020, with the start of the dry season, and AOD values of greater than two are found by the end of March 2021, indicative of very high aerosol loading. Increasing new COVID-19 weekly cases and AOD values are found in the dry season, but COVID-19 new cases begin to decrease in Nigeria by February even with high AOD values (Figure 3d). In Angola, we find the highest AOD values beginning in July of 2020 and lasting through November 2020 (Figure 3e). The rise in new COVID-19 cases begins to increase at the end of June and reaches a maximum value at the end of November. In Angola, the lag in maximum COVID-19 cases occurs one to two months after the maximum AOD values are found, unlike the AOD values in Nigeria (Figure 3d). Low correlations between countrywide AOD with COVID-19 are found for Cote D'Ivorie, Nigeria and Angola during the wet and dry seasons (Tables 1 and 2).

Closely related to AOD in the dry season is the production of black carbon aerosols from biomass burning. We consider only Angola, Cote D'Ivorie, Nigeria, and Senegal in the weekly fire count as a proxy for determining biomass burning activity. Figures 4a–4c shows the weekly fire count in Senegal, Cote D'Ivorie, and Nigeria with large fire counts occurring during January–March 2020, prior to the COVID-19 pandemic. Fire counts are negatively correlated and significant at the 95% confidence level to COVID-19 cases during the first COVID-19 wave (wet season) in Cote D'Ivorie, Nigeria, and Senegal as decreasing fires occur while there is increasing weekly COVID-19 cases (Table 1). The first COVID-19 wave occurs during the dry season in Angola and fires are negative correlated (−0.80) and significant at the 95% confidence level to weekly COVID-19 cases (Table 1).

The return to seasonal fires occurs from November 2021 through February of 2021, with an increase in fire counts in three countries when COVID-19 cases are increasing (Figure 1). Nigeria has the highest fire count relative to Cote D'Ivorie and Senegal. During the first 2 months of 2020, the pattern of fires closely matches those of the AOD. In late 2020, fire counts increased during the second COVID-19 wave in Senegal, Cote D'Ivorie, and Nigeria; however, the initial fires occurred in November of 2021 in Senegal prior to the start of the second COVID-19 wave. Negative correlations are found in Senegal and Cote D'Ivorie, during the second wave; however, a larger positive correlation (0.41) between fire count and COVID-19 new cases is found in Nigeria for the second COVID-19 wave (Table 2). In Angola, a large increase in fire counts began in May of 2020, following a similar pattern to the AOD, with a maximum number of fire counts occurring prior to the largest numbers of weekly COVID-19 cases, leading to a negative correlation (Figure 4d, Table 1).

Next, we examine NO_2 column values, which would be reflective of anthropogenic pollution sources such as urban pollution on an annual basis, biomass burning during the dry season, soils and lightning during the wet season. Figures 5a–5d shows the column NO_2 and COVID-19 new cases for Abidjan, Cote D'Ivorie, Dakar, Senegal, Abuja, Lagos, and Kano, Nigeria. Increases in column NO_2 at Dakar, Senegal, follow that of AOD and fire count, with a winter season peak that declines during the spring of 2020, followed by an increase in NO_2

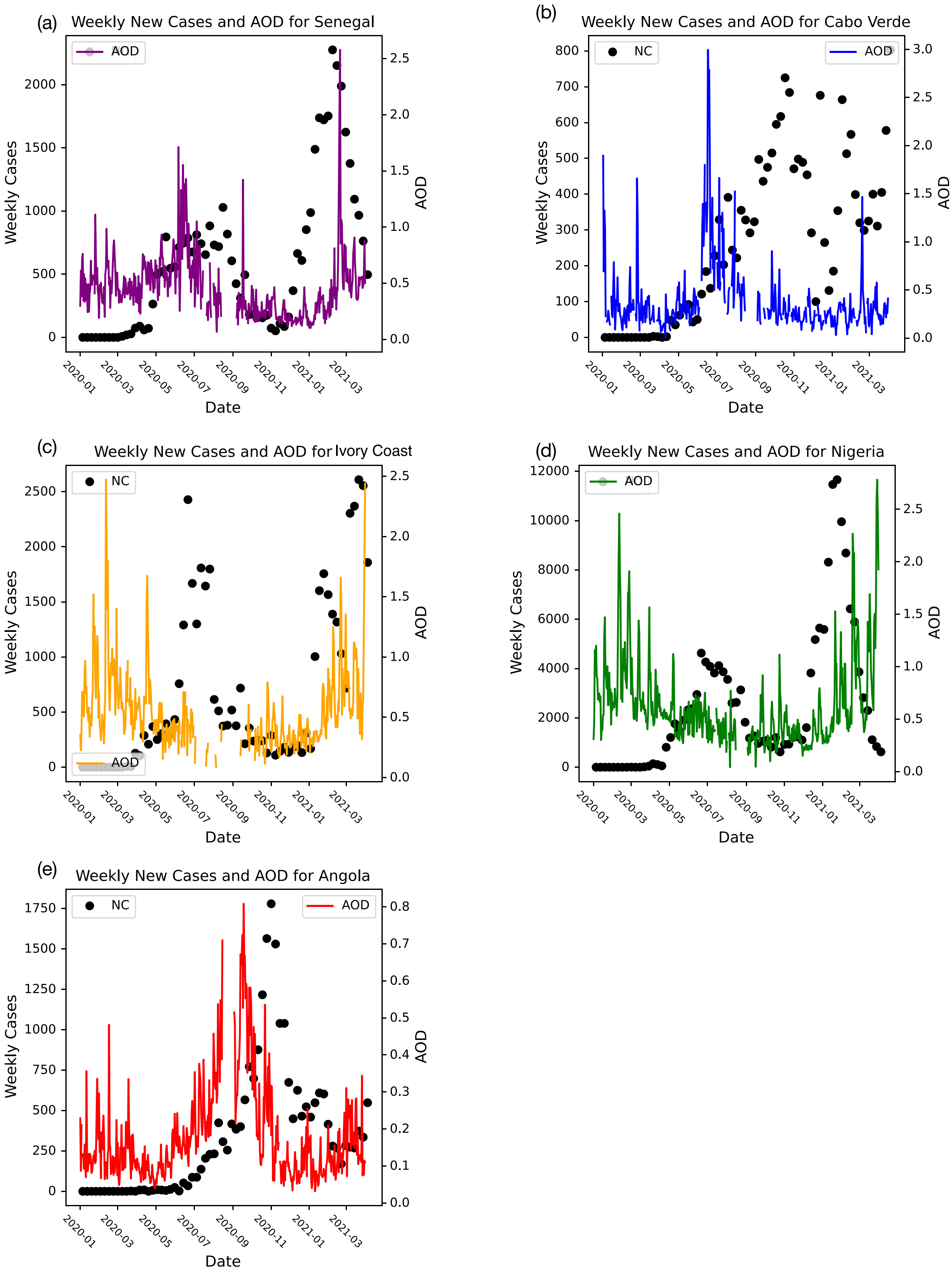

Figure 3. 1 January–31 March 2021 weekly confirmed new cases and weekly AOD for: (a) Senegal; (b) Cabo Verde; (c) Cote D'Ivorie; (d) Nigeria, (e) Angola.

during November of 2020, which then declines in March 2021 (Figure 5a). We also find a rapid rise in Dakar's NO_2 column values from May through August of 2020 as COVID-19 cases increase during the wet period of the first wave (Figure 5a), leading to a positive correlation (Table 1), but a negative correlation which is statistically significant, during the second wave (Table 2). The increase in summer values could be linked to increased

Table 2
Wave 2 Correlations Between New COVID-19 Cases and Atmospheric Variables (Correlation With New Cases)

	$PM_{2.5}$	Temp	Fire count	NO_2 column values	AOD	RHUM	Precip
Dakar, Senegal	0.33	−0.67*	−0.22	−0.53*	0.39**	−0.33	0.29
Praia CV	−0.20	−0.30	n/a	n/a	0.07	0.15	n/a
Ibadan Nigeria	0.54*	0.04	0.41**	n/a	−0.15	−0.17	−0.40**
Lagos Nigeria	n/a	n/a	0.41**	0.78*	−0.15	n/a	−0.40**
Abuja Nigeria	n/a	n/a	0.41**	0.93*	−0.15	n/a	−0.40**
Kano Nigeria	n/a	n/a	0.41**	0.03	−0.15	n/a	−0.40**
Cote D'Ivorie	n/a	n/a	−0.23	−0.67*	−0.22	n/a	−0.13
Luanda	n/a	n/a	0.61*	0.15	0.43*	n/a	−0.18

urban pollution and nitrogen releases from the soil at the start of the wet season. NO_2 column values in Dakar then increase in November 2020, which occur with the increase in fire counts associated with biomass burning, reaching the maximum values between December 2020 and February 2021 before declining, with the largest

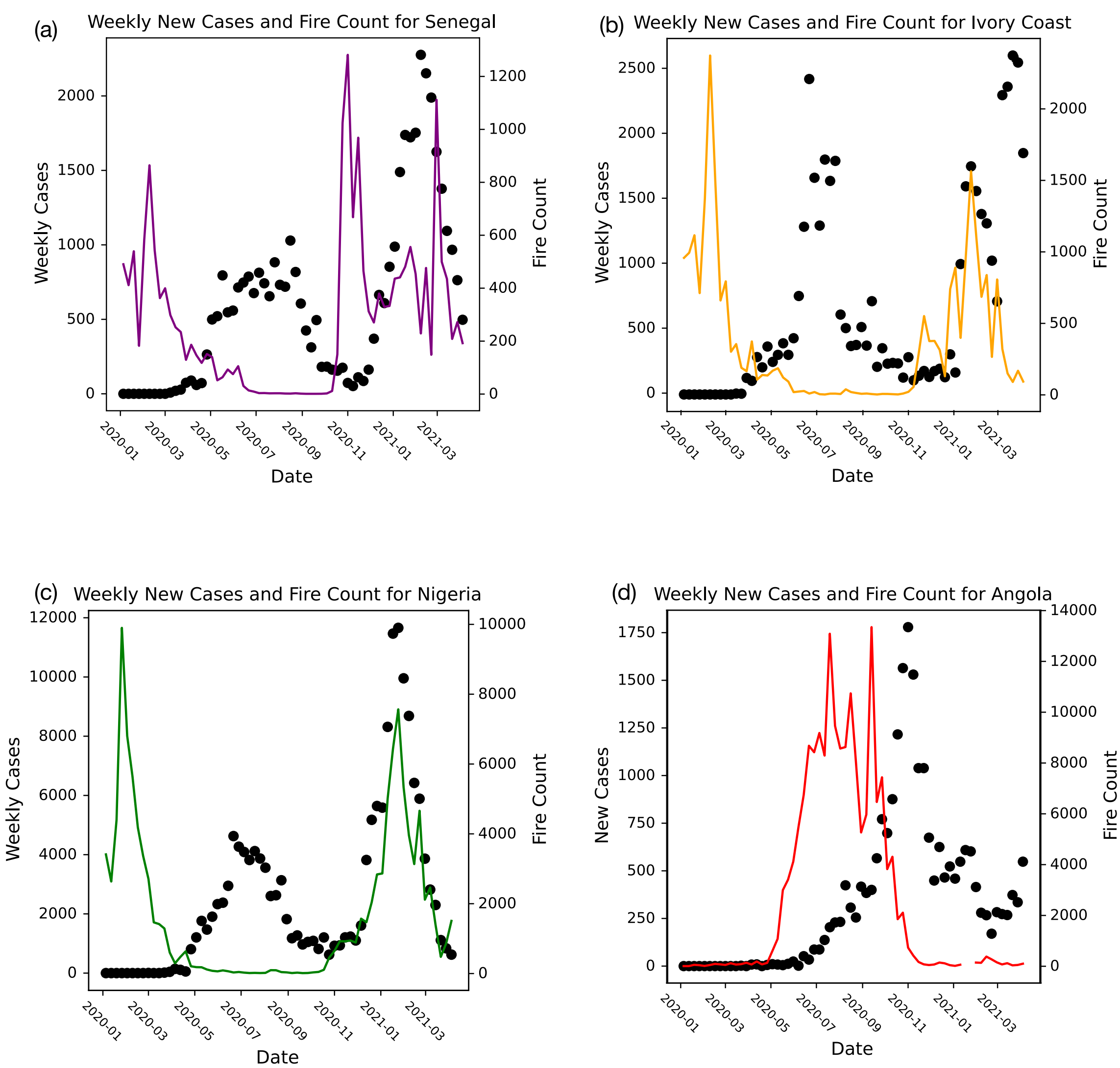

Figure 4. 1 January–31 March 2021 weekly confirmed new cases and weekly fire count for: (a) Senegal; (b) Cote D'Ivorie; (c) Nigeria, (d) Angola.

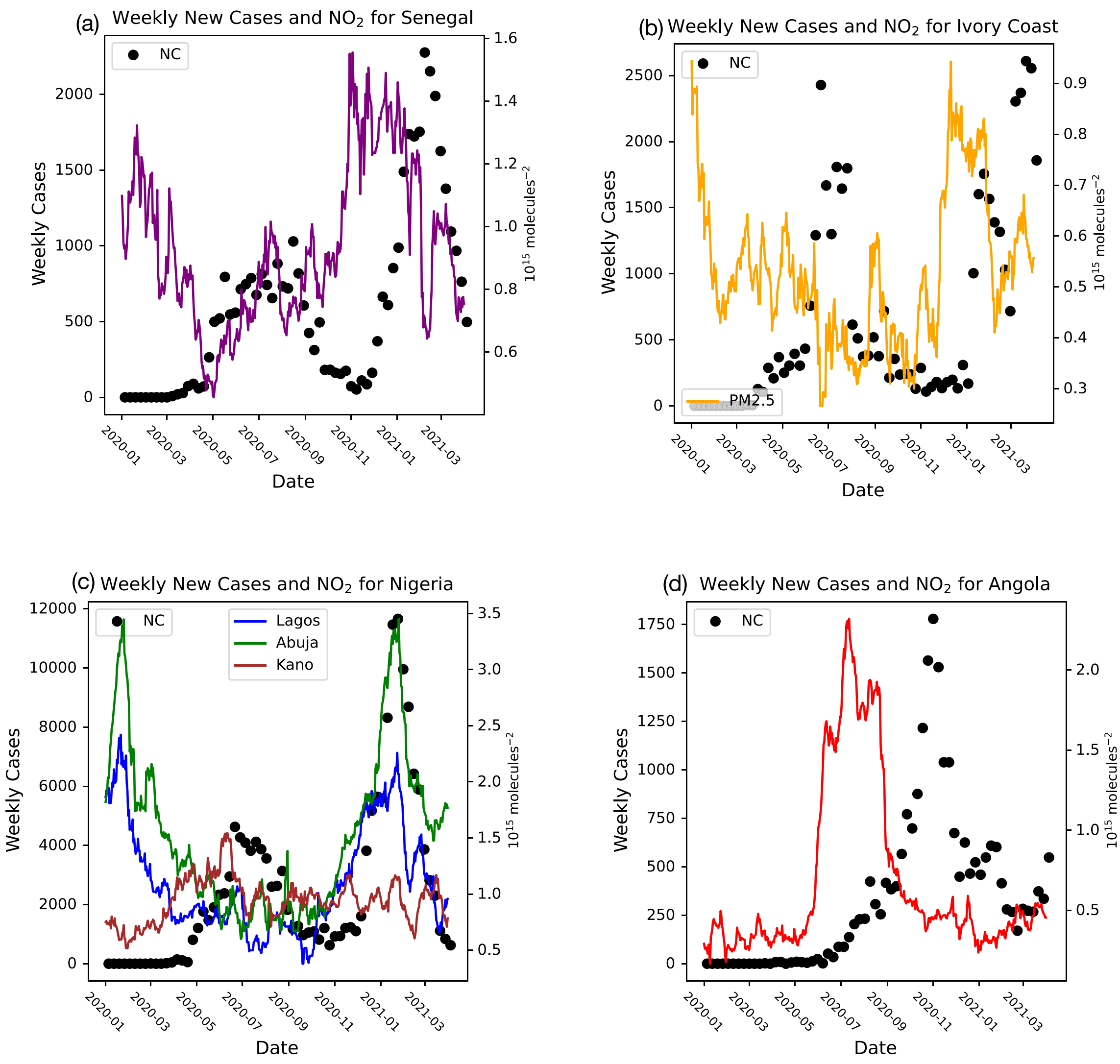

Figure 5. 1 January 2020–31 March 2021 weekly confirmed new cases and weekly column NO_2 values for: (a) Dakar, Senegal, (b) Abidjan, Cote D'Ivorie, (c) Lagos, Abuja and Kano, Nigeria, (d) Luanda, Angola. Units are 1,015 molecules cm^{-2}.

NO_2 column values occurring prior to COVID-19 weekly peak (Figure 5a). This leads to a moderate negative correlation which is statistically significant (Table 1). Abidjan, Cote D'Ivorie shows a similar temporal pattern to Dakar, with the largest values during January 2020 and declining before reaching the lowest values at the peak of the first wave leading to a negative correlation with COVID-19 new cases (Figure 5b, Table 1).

NO_2 column values for Abuja, Kano, and Lagos are shown in Figure 5c, with NO_2 column values being the largest for Abuja, although Lagos has larger industrial activities and urban traffic due to its size. However, fire locations are not located at the coast near Lagos, but throughout the southern and central parts of Nigeria and upstream in nearby countries transporting more NO_2 enriched air toward Abuja instead of Lagos. The timing for increases in NO_2 values in Lagos and Abuja coincide with increasing fire counts, suggesting that biomass burning, and not urban traffic, is the primary source of NO_2. This is also suggestive when observing that no significant increases in column NO_2 values are found in Kano, Nigeria, which is in a semi-arid environment with dust from the Bodele Depression being the primary source of PM during the dry season. Lagos and Abuja, Nigeria have the highest NO_2 column values during February 2020 and decrease throughout the spring, reaching their lowest values at the peak of the first COVID-19 wave (Figure 5c). The return of seasonal biomass burning after November, 2020, shows that NO_2 column values are positively correlated and statistically signifcant (0.78) to weekly new COVID-19 cases during the second wave in Nigeria (Table 2). NO_2 values at Lagos are positively correlated to fires (0.30)

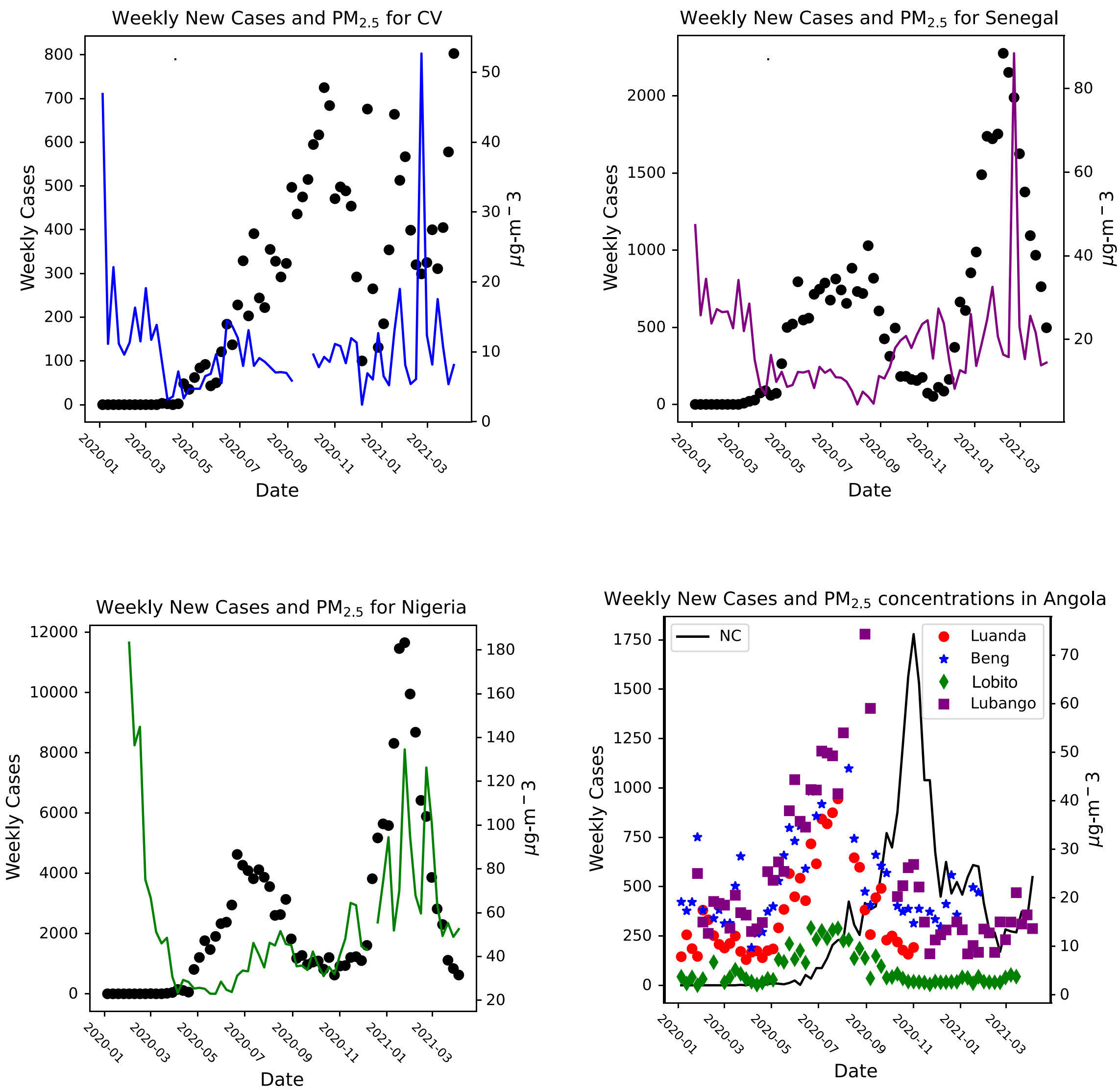

Figure 6. 1 January 2020–31 March 2021 weekly confirmed new cases and weekly $PM_{2.5}$ concentrations for: (a) Praia, Cabo Verde; (b) Dakar, Senegal, (c) Ibadan, Nigeria, (d) Luanda, Lobito, Benguela and Lubango, Angola. Units are μg m^{-3}.

but negatively correlated to AOD (−0.4) during the second wave because of a lag between the two variables. In the Southern Hemisphere, NO_2 values at Luanda, Angola overlap with fire count and are positively correlated (0.76) but negatively with AOD (−0.11). However, NO_2 and fire counts peak much earlier than the number of weekly new COVID-19 cases (Figures 4d and 5d). Consequently, biomass burning signature, with the maximum values occurring prior to the peak in COVID cases in November 2020, producing a negative correlation (−0.80) between weekly new COVID-19 cases and NO_2 column values (Figure 5d, Table 1).

3.4. Purple Air $PM_{2.5}$ Concentrations, Temperatures, and New COVID-19 Cases

Next, we examine in-situ purple air sensor measurements and weekly new COVID-19 cases. Figures 6a–6d shows the weekly $PM_{2.5}$ concentrations and weekly new COVID-19 reported cases across Praia, Cabo Verde; Dakar, Senegal; Ibadan, Nigeria; Luanda, Benguela, Lobito, and Lubango, Angola. Although, the poorest air quality in Praia occurs January–March 2020 and 2021 there is limited temporal coherence with weekly new COVID-19 cases (Figure 6a). There is a negative correlation (−0.29) between weekly new COVID-19 cases and $PM_{2.5}$ concentrations during the first covid wave (Table 1) in Praia. During the second COVID-19 wave, there is a positive correlation (Table 2) between weekly new COVID-19 cases and $PM_{2.5}$ concentrations (−0.20), with an increase in the number of weekly COVID-19 cases after a significant dust event in February of 2021 (Figure 6a, Table 2). Dakar, Senegal, shows a similar pattern of $PM_{2.5}$ concentrations with the highest values occurring during dry seasons of January–March, 2020 and November–March 2020–2021 (Figure 6b). During the first COVID-19 wave in the wet season, $PM_{2.5}$ concentrations are negatively correlated (−0.50) and statistically significant to weekly new COVID-19 with falling values $PM_{2.5}$ and rising values of new COVID-19 cases (Figure 6b). The increase in $PM_{2.5}$ concentrations during after November 2020 with the advent of the dry season is positively correlated (0.33) to new COVID-19 cases (Figure 6b).

Ibadan, Nigeria, has the highest weekly $PM_{2.5}$ concentrations during the dry seasons of February–March 2020 and November 2020–March 2021, which is likely a combination of biomass burning and dust intrusions from the Bodele depression (Figure 6c). Unlike, Dakar, a slight increase in $PM_{2.5}$ concentrations during NH summer is positively correlated to correlated (0.28) to new COVID-19 cases during the first wave. Between, November 2020 and March 2021 we find a rise in $PM_{2.5}$ concentrations at Ibadan, most likely linked to biomass burning and dust intrusions with weekly values exceeding 100 $\mu g\ m^{-3}$ during the period. The increase in $PM_{2.5}$ concentrations after November 2020 are coherent with increases in fire counts (Figure 4c), NO_2 column values (Figure 5c), and new COVID-19 weekly cases. $PM_{2.5}$ concentrations and new COVID-19 weekly cases are positive correlated and statistically significant (0.54) at Ibadan during the second wave (Table 2).

In the Southern Hemisphere during the first COVID-19 wave in Angola, $PM_{2.5}$ concentrations peaked several months prior to the highest reported weekly COVID-19 cases. The highest $PM_{2.5}$ concentrations are found at Lubango relative to Luanda, Benguela, and Lobito, but all stations peak between May and September (Figure 6d). The increase in $PM_{2.5}$ concentrations occurs when fires counts and NO_2 column values increase and reach their maximum values before the peak in reported weekly new COVID-19 cases (Figures 4d, 5d, 6d). $PM_{2.5}$ concentrations and new COVID-19 weekly cases are negatively correlated at all locations, however the highest negative correlations which are statistically significant occur at Liboto and Luanda (Table 2).

Figures 7a–7d shows the Purple Air and Clarity weekly temperatures and reported COVID-19 cases at specific locations in Cabo Verde, Senegal, Nigeria, and Angola. During the first COVID-19 wave, Praia, Cabo Verde shows increasing temperatures during the period when weekly new COVID-19 cases are increasing (Figure 7a), but correlations are very weak (0.03). In the second wave (January 2021–March 2021), there is a negative correlation (−0.29) between temperature and COVID-19, as cooler temperatures are found during the dry season in Praia.

Dakar, Senegal, shows a slight decrease in temperatures prior to the first COVID-19 wave but a general warming trend is found during the first wave leading to a positive correlation between COVID-19 weekly cases and temperature (0.44) which is statistically significant, similar to Diouf et al. (2021). During the second COVID-19 wave between November 2020 and 31 March 2021, a decreasing temperature trend is found, with temperatures being negatively correlated (−0.67) and statistically significant (Figure 7b). Temperatures in Ibadan, Nigeria, the warmest relative to the other stations but during the first COVID-19 wave in the wet season a pattern of cooling temperatures occur relative to new weekly COVID-19 cases producing a negative correlation (−0.494) and statistically significant (Table 1). As the rainy season ends an increase in weekly temperatures are found but produce only a smaller positive correlation (0.04) with new weekly COVID-19 cases (Table 2) in agreement with Diouf et al. (2021). In Angola, during the first wave (dry season) the four stations tend to show cooler temperatures prior to rapidly increasing weekly COVID-19 cases during the biomass burning season, but a warming trend as the COVID-19 wave is peaking during September–November. Consequently, we find positive correlations among three cities between weekly temperatures and new COVID-19 case for Lobito (0.54), Benguela (0.33), and Lubango (0.33) but a negative correlation for Luanda (0.20) for the second wave (Table 2). We also show in Tables 1 and 2 that relative humidity is positively correlated and statistically significant to new COVID-cases (0.44) during the first COVID-19 wave only at Ibadan, Nigeria (Table 1).

Table 3 summarizes air quality at Purple Air stations during the two COVID-19 waves using US air quality standards in Cabo Verde, Nigeria, Senegal, and the first COVID-19 wave in Angola. Average $PM_{2.5}$ concentrations and the percentage of days with good, moderate, unhealthy for sensitive groups (USG) and unhealthy $PM_{2.5}$ concentrations are computed. The dry season in Cabo Verde, Nigeria, and Senegal have higher mean $PM_{2.5}$ concentrations during the second COVID-19 wave. In the first COVID-19 wave, $PM_{2.5}$ concentrations exceed 20 $\mu g\ m^{-3}$ in Angola except in the coastal location of Lobito. In Praia and Dakar, good air quality values are found for most days during the first COVID-19 wave good air quality, however, there were zero days of good air quality

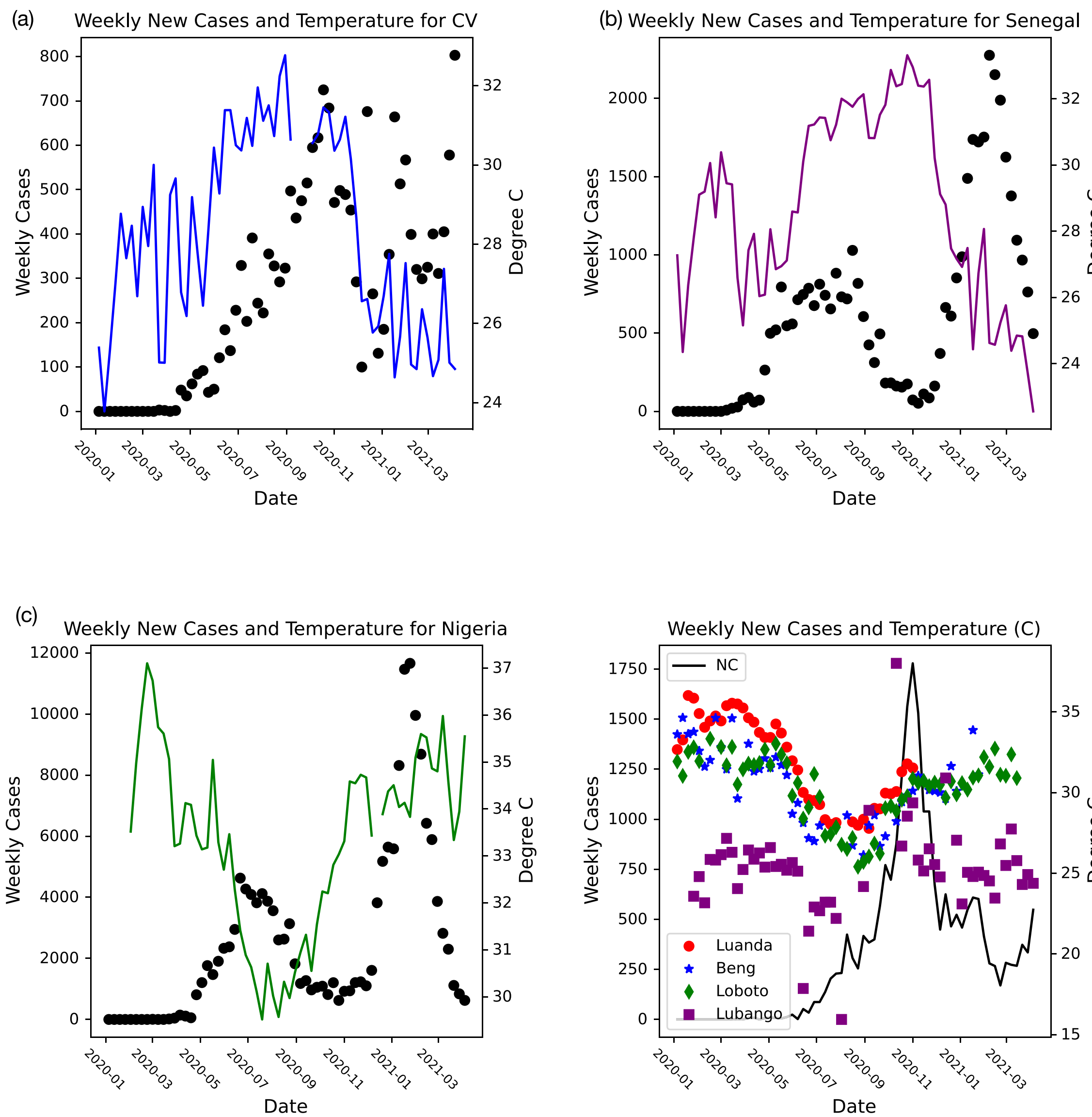

Figure 7. 1 January 2020–31 March 2021 weekly confirmed new cases and weekly temperatures for: (a) Praia, Cabo Verde; (b) Dakar, Senegal, (c) Ibadan, Nigeria, (d) Luanda, Lobito, Benguela and Lubango, Angola. Units are °C.

in Ibadan. In Angola, Lobito registered 80% of good air quality days, while the capital, Luanda, had 31% good air quality during the first wave, with the majority of days having moderate and USG values. Benguela and Lubango also show that the majority of days have moderate and USG air quality.

During the second COVID-19 wave in Praia, good to moderate air quality is found (Table 3), with only one significant dust event in February 2021 leading to 2.3% of unhealthy days (>55.5 μg m^{-3}). In Dakar, Senegal, the majority of days (72.1%) during the second COVID wave are considered moderate, with approximately 11% of the days having USG air quality with daily $PM_{2.5}$ in excess of 35.5 μg m^{-3} (Table 3). Saharan dust was the primary source of particulate matter in Praia and Dakar during the second COVID-19 wave. Ibadan, Nigeria, has much worse air quality relative to the other PA stations, even during the wet season when the first COVID-19 wave occurred. During the first COVID-19 wave, 51% of the days in Ibadan were moderate, while the other 49% were USG with daily values exceeding 35.5 μg m^{-3}. During the second COVID-19 wave, nearly 88% of the days were USG with $PM_{2.5}$ concentrations in excess of 35.5 μg m^{-3}, and 65% of the days having unhealthy $PM_{2.5}$ concentrations exceeding 55.5 μg m^{-3}. The sources of $PM_{2.5}$ in Ibadan during the second wave are most likely a combination of local pollution, biomass burning, and Saharan dust. The episodic patterns in $PM_{2.5}$ concentrations and

Table 3
Mean Purple Air $PM_{2.5}$ Concentrations During Wave 1 and 2, and Air Quality Standards for $PM_{2.5}$; Good (0–12 μg m^{-3}); Moderate (12–35.5 μg m^{-3}) Unhealthy for Sensitive Groups (35.5–55.5 μg m^{-3}); Unhealthy (>55.5 μg m^{-3})

Location of PM or Clarity sensor	Interval dates (wave 1)/(wave 2)	Mean $PM_{2.5}$ concentration	Percent good days) (wave 1/wave 2)	Percent moderate (wave 1/wave 2)	Percent UHS (wave 1, wave 2)	Percent unhealthy (wave 1, wave 2)
Praia, Cabo Verde	(6 June–29 November)/(3 January–31 March 2021)	9.6/13.3	80/66.3	66.3/29.1	0/2.3	0/2.3
Dakar, Senegal	(27 April–13 September)/(1 November 2020–31 March 2021)	9.9/22.5	72.9/17	27.1/72.1	0/7.5	0/3.4
Ibadan, Nigeria	(27 April–27 September)/(1 November 2020–31 March 2021)	35.4/70.9	0/0	51/2.2	43/32.8	6/65
Luanda, Angola	(28 June–22 November)	23.6	30.6	44.1	21.6	3.6
Lobito, Angola	(28 June–22 November)	7.2	79.7	20.3	0	0
Benguela, Angola	(28 June–22 November)	27.0	0.9	81.5	10.2	7.4
Lubango, Angola	(28 Jun–22 November)	34.1	11.1	47.2	29.2	12.5

AOD are suggestive of Bodele dust intrusions, while the steady number of fires and NO_2 column values across Nigeria and in Lagos are strongly suggestive of seasonal biomass burning. High $PM_{2.5}$ concentrations throughout the first and second COVID-19 waves in Ibadan are higher than the US EPA and WHO daily recommended guidelines. This level of poor air quality is likely to have negative health outcomes for those who contracted COVID-19 and with confounding factors such as respiratory and cardiovascular disease.

4. Discussion and Conclusion

We have examined the linkages between weekly new COVID-19 cases and deaths with satellite-based AOD, fire locations, NO_2 column estimates, precipitation for Angola, Cabo Verde, Cote D'Ivorie, Nigeria, and Senegal for 1 January 2020 through 31 March 2021. In addition, we have used low-cost purple air sensors (Liu et al., 2020) to monitor the particulate matter and temperature during the COVID-19 pandemic for selected African countries in real-time (Ogunjo et al., 2022). The findings show that the COVID-19 waves of 2020 and early 2021 occurred during the wet and dry seasons, respectively, in Cabo Verde, Cote D'Ivorie, Nigeria, and Senegal. In Angola, the first COVID-19 peak occurred one to two months after the biomass burning season had peaked in 2020. Consequently, we find negative correlations between weekly $PM_{2.5}$ concentrations and weekly new COVID-19 cases during Angola's dry season when compared to positive correlations in Cabo Verde, Nigeria, and Senegal during its dry season. Correlations between COVID-19 weekly new cases and PA temperatures in Senegal and Nigeria are in agreement with those of Diouf et al. (2021) during the first COVID-19 wave showing positive and negative correlations, respectively. Positive correlations between weekly COVID-19 weekly cases, and PA relative humidity were also positive in the first wave, in agreement with Diouf et al. (2021). Overall, the highest correlations occurred between weekly new COVID-19 cases meteorological and air quality variables occurred in the dry season.

Desert dust is the most likely source of elevated $PM_{2.5}$ concentrations during the dry season in Senegal, Cabo Verde, and across the Sahelian region which is expected to increase respiratory disease on an annual basis. Further, to the south, at Ibadan, Nigeria multiple sources of pollution are likely responsible for high $PM_{2.5}$ concentrations. In Nigeria and Angola, high concentrations of particulate matter are found with high NO_2 column values during the dry season and suggestive of a biomass burning signature. It is also likely that surface CO mixing ratios and secondary pollutant O_3 mixing ratios are elevated because of biomass burning but not measured in this study.

High $PM_{2.5}$ concentrations and NO_2 column values have been linked to COVID-19 cases, its spread, and COVID-19 mortality in Europe, China, and America (Liang et al., 2020). Shao et al. (2022) found a 16-day lag between $PM_{2.5}$ and COVID-19 mortality. In this study, mean PM concentrations during the dry season are higher than in the wet season, and the number of days with poor air quality is increased, leading to the expectation of increased COVID-19 cases and more serious COVID-19 cases. In Nigeria, we expect that high PM and NO_2 column values could increase the seriousness of COVID-19 leading to fatalities. Moreover, southern and central parts of Nigeria are subject to the "double hit" hypothesis producing negative health outcomes and even mortality, especially with COVID-19 variants that negatively impact the respiratory system (Arora et al., 2021). However, we have not examined the COVID-19 mortality because many factors could impact these values, including the state of public health care facilities, the locations of the deaths, and the wide use of verbal autopsies for determining the cause of death, especially in rural zones. We expect a varying lag in COVID-19 mortality across the five countries based on the pollution levels and the weekly new COVID-19 cases. Future analysis will focus on lag correlations with low-cost air pollution measurements.

In following the pandemic into 2022, we found at least two additional COVID-19 waves in all five countries. During 2021, a wet season, COVID-19 waves were present in Senegal, Nigeria, and Cote D'Ivorie, but occurred during the peak of the monsoon season (September) in association with the Delta variant. From December 2021 through February 2022, another COVID-19 wave occurred in association with the Omicron variant. A mixture of environmental conditions and social behaviors may be responsible for the observed COVID-19 waves, for example, there could be more indoor activity during poor air quality events in the dry season and during rainy periods of the wet season because of floods and vector borne disease, thereby increasing COVID-19 transmission. However, there is uncertainty because of low COVID-19 testing in some countries, and consequently, new cases and fatalities are likely underestimated.

This study has several limitations that are related to health and environmental data. First, there is significant uncertainty because of low COVID-19 testing in some countries which may have focused on airports and costs associated with testing. Second, some countries did not consistently report new cases and fatalities to the WHO and consequently, new cases and fatalities are likely underestimated. Third, limited vaccines sent to the countries in this study have not been accounted for in this work. Another source of pollution uncertainty arises from the small number of PM stations across the study area. Because air quality varies spatially across each country and the various islands of Cabo Verde daily values of PM are more representative for large-scale pollution such as Saharan dust events and biomass burning during the dry seasons in West Africa (December–March) and Angola (June–October). When we observed coherent satellite estimates of poor air quality (fire count, AOD, column NO_2) with surface PM, our confidence level increased, especially for Nigeria and Angola during the dry season. We have not accounted for government lockdown activities in the five countries and their impacts on air quality, however, large-scale transport of PM from the Sahara and biomass burning is a major source of PM, with government lockdowns having no effects on downstream locations.

The lack of PM stations in monitoring pollution and its connections to COVID-19 in Sub-Saharan Africa will be a challenge until the COVID-19 pandemic has finally come to an end. Until then, PM and other pollution measurements should be closely monitored and shared with the public health system along with decision-makers to ensure that pollution and COVID-19 outbreaks are taken into account. Whenever possible, air quality standards should be improved, although large scale-biomass burning would require regional cooperation and Saharan dust events cannot be controlled but can be forecasted (Jenkins & Diokhane, 2017) and communicated with the public. Based on our results, we believe that during the dry season, multiple sources of air pollution ($PM_{2.5}$, NO_2), pose the greatest health threat to populations in West and Southern Africa when COVID-19 is present.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data which includes COVID-19 and atmospheric variables produced in this study are publicly available through the Pennsylvania State University Scholarsphere at https://doi.org/10.26207/tfqg-9486.

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