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Air transportation as a puzzle piece of COVID-19 in Africa?

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ABSTRACT

COVID-19 has hit our society hard, with more than 242 million cases reported worldwide and more than 4.9 million directly related fatalities. The role of Africa throughout the pandemic has been puzzling, since the African continent seems to have gone through the pandemic better than other continents; clearly better than predicted by the public during the emergence of COVID-19 one year ago. While several factors have been proposed in the literature to explain the unexpected role of Africa, including a relatively young population, more historical-driven preparedness to other types of coronavirus and diseases, and a limited amount of testing, the puzzle is not considered to be solved. In this study, we aim to answer the question whether air transportation indicators can support us in explaining the evolution of COVID-19 in Africa? Using flight data for the year 2020, we explore how changes in the air transportation system correlate with evolution of epidemiological indicators. Our results suggest that air transportation could indeed play a critical role for the spread of COVID-19 in Africa as well. Overall, we hope that our analysis contributes towards a better understanding of COVID-19 and the role air transportation plays in an under-researched region of the world.

1. Introduction

The mobility of our society has significantly contributed to the increased risk of epidemic spreading, mainly driven by the efficiency and affordability of long-distance travel. History has several examples which show the extreme importance of air transportation for a contagion to spread successfully (Brockmann & Helbing, 2013; Budd, Bell, & Brown, 2009), with examples from the recent two decades including SARS 2003 (Likhacheva, 2006), MERS 2012 (Zaki, van Boheemen, Bestebroer, Osterhaus, & Fouchier, 2012), and Ebola 2014 (Bogoch et al., 2015). In the latter three cases, we were able to avoid a transition from an epidemic outbreak to a full pandemic, mostly by coordinated actions of relevant policy makers and stakeholders. For COVID-19, however, the critical time window for constraining the spread was missed (Sun, Wandelt, & Zhang, 2021b). The pandemic has extreme effects on our society, with more than 289 million cases reported and more than 5.4 million directly related fatalities worldwide, by the end of the year 2021.

At the outbreak of COVID-19, the African continent was predicted to face a tremendous number of cases and fatalities. Looking back, however, it seems like Africa has shown a significantly different epidemiological profile than expected. A comparative visualization among the number of daily reported COVID-19 cases in Africa, Europe, and the United States is shown in Fig. 1. For a long time, there has been an absence of exponential growth in several African countries; and much lower rates of both the confirmed cases and fatalities were reported (Bamgboye et al., 2020). Africa is accounting for about 3% of the world's confirmed cases and deaths, despite being the second most-populated continent on Earth, covering about 17% of the world's population. Moreover, the genesis of COVID-19 in Africa is reportedly later than that for other continents and less renal complications have been reported in Africa. Accordingly, there are several open questions regarding the role and performance of Africa under COVID-19. Recent studies have coined these questions as being an important *puzzle* to solve (Maeda & Nkengasong, 2021; Nordling, 2020); see also Winning (2020). Several explanations for the unexpected performance of Africa have been discussed, including the relatively young population (Diop, Ngom, Biyong, & Biyong, 2020), more historical exposure to other types of coronavirus with an accompanying higher natural defense mechanism (Nordling, 2020), and a head start having learned from earlier epidemic outbreaks in Africa (Ondoa et al., 2020).

On the other hand, a recent study on the prevalence of anti-SARS-

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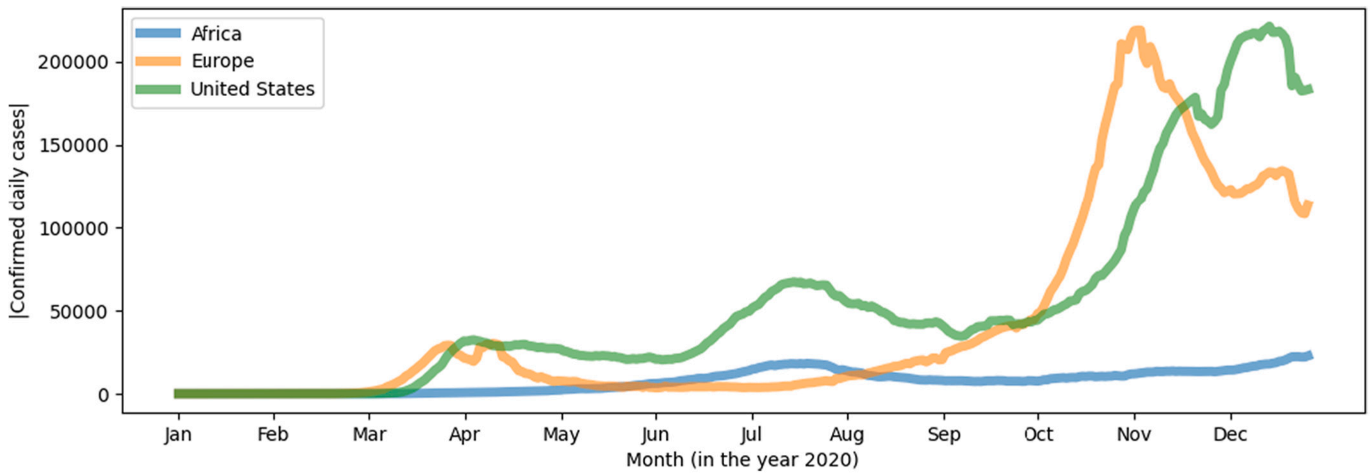

Fig. 1. Visualization for the daily number of confirmed cases for Africa, Europe, and the United States.

CoV-2 immunoglubolin G within parts of the Kenyan population has revealed that exposure is much more extensive than expected from the official reports (Uyoga et al., 2020). Therefore, it cannot be stated with confidence that the African continent went through the pandemic much better than other countries. While the lack of consistent reports and large-scale coverage makes it hard to draw ultimate conclusions, the puzzled (and seemingly obvious) differences between Africa and other continents do suggest that more study of the COVID-19 pandemic in Africa is warranted (Bearak & Paquette, 2020; Chakamba, 2020); see also Section 2 below. Furthermore, a recent development in Africa indicated the emergence of new coronavirus variants (as, for instance, Omicron), which not only leads to a larger number of infections and deaths, but also poses significant threats to other continents. Therefore, a better understanding of the African continent is essential to better fight COVID-19 and future pandemics at a continental and worldwide scale.

We contribute to the study of the African continent under COVID-19 by taking a different perspective compared to the literature. We investigate the changes in air connectivity and ask whether there are significant differences observable on the African continent compared to those in other regions of the world. Air transportation-related activity directly supports almost eight million jobs and more than 63 billion USD of continental economic value, covering almost 3% of the total GDP of all African countries in 2018. Given the long-distance connections to Asia, Europe, and the United States, air transportation contributes a substantial share to the tourism-related economies in Africa. While these long-distance connections are essential for economical reasons, they also open the door for the spreading of a contagion/disease. Accordingly, better understanding the mutual influence between aviation and African COVID-19 development is an interesting case for research analysis.

In this study, we take actual flight data for the year 2020 and investigate how the number of confirmed cases in African countries evolved over time and whether we can possibly find an explanation rooted in the regional flight connectivity. We report aggregated data for 54 African countries and perform an in-depth analysis of the top-20 countries ranked by the total population. These 20 countries are highlighted in Fig. 2, together with locations and degree of traffic for the airports on the African continent. Our selection of the countries is representative of a wide range of geopolitical regions on the continent. Alternatively, we could have selected countries based on the degree of flight activity, but this would have possibly led towards a bias for African countries with high international flight activity. Based on the findings in our study below, we conclude that air transportation could indeed play a critical role for the spread of COVID-19 in Africa as well, which is a result complimentary to those in the existing literature. Therefore, it is hoped that our study on the relationship between COVID-19 and air transportation for Africa contributes towards resolving the continent's COVID-19 puzzle.

The remainder of this study is structured as follows. Section 2 provides an overview on the recent literature regarding COVID-19 and air transportation, together with studies that discuss the role of Africa throughout COVID-19. Section 3 reports briefly the evolution of COVID-19 on the African continent in comparison to other parts of the world. This section sets the baseline for the need to have a better understanding of the drivers behind COVID-19 in Africa. Section 4 describes the evolution of the African air transportation system throughout the pandemic. Section 5 concludes this study and provides a set of recommendations for future work.

2. Literature review

Since the emergence of COVID-19, many studies have been published, with the aim to analyze and better understand the dynamics underlying COVID-19, at different time scales, spatial regions, and focuses of interest. It is beyond the scope of this study to exhaustively list and review all these papers. We refer the reader to a recent survey which has the goal to provide an overview on research regarding air transportation and COVID-19 (Sun, Wandelt, Zheng, & Zhang, 2021). Below, we provide a brief overview on the most relevant studies regarding air transportation analysis, epidemic spreading through air transportation systems, and studies specific to the African continent, respectively.

2.1. Air transportation analysis

Several studies are concerned with the temporal evolution of air transportation. Sun, Wandelt, and Zhang (2020) performed a complex network-based analysis of the impact that COVID-19 had on aviation during early periods of the year 2020. Strict flight restrictions were observed at the global level, mostly executed on international connections. Similarly, Suzumura et al. (2020) analyzed the number of flights during COVID-19 as a time series for the first few months in the year 2020 and discussed these results in context with workforce occupation in different sectors. Nižetić (2020) performed an impact study with a focus on Europe for the first four months of the year 2020. Sun, Wandelt, and Zhang (2021b) found that flight bans in Europe came particularly late and several domestic air transportation networks were significantly less impacted than one would have expected. Albers and Rundshagen (2020) investigated the first five months of 2020 and derived a classification of the reactions observable for individual airlines. Budd, Ison, and Adrienne (2020) showed that operational changes to flights, fleet rationalization, and staff reduction were prevalent among airlines early in the year 2020. Other research specific to airlines includes da Silveira Pereira and Soares de Mello (2021) and Bombelli (2020), who analyzed

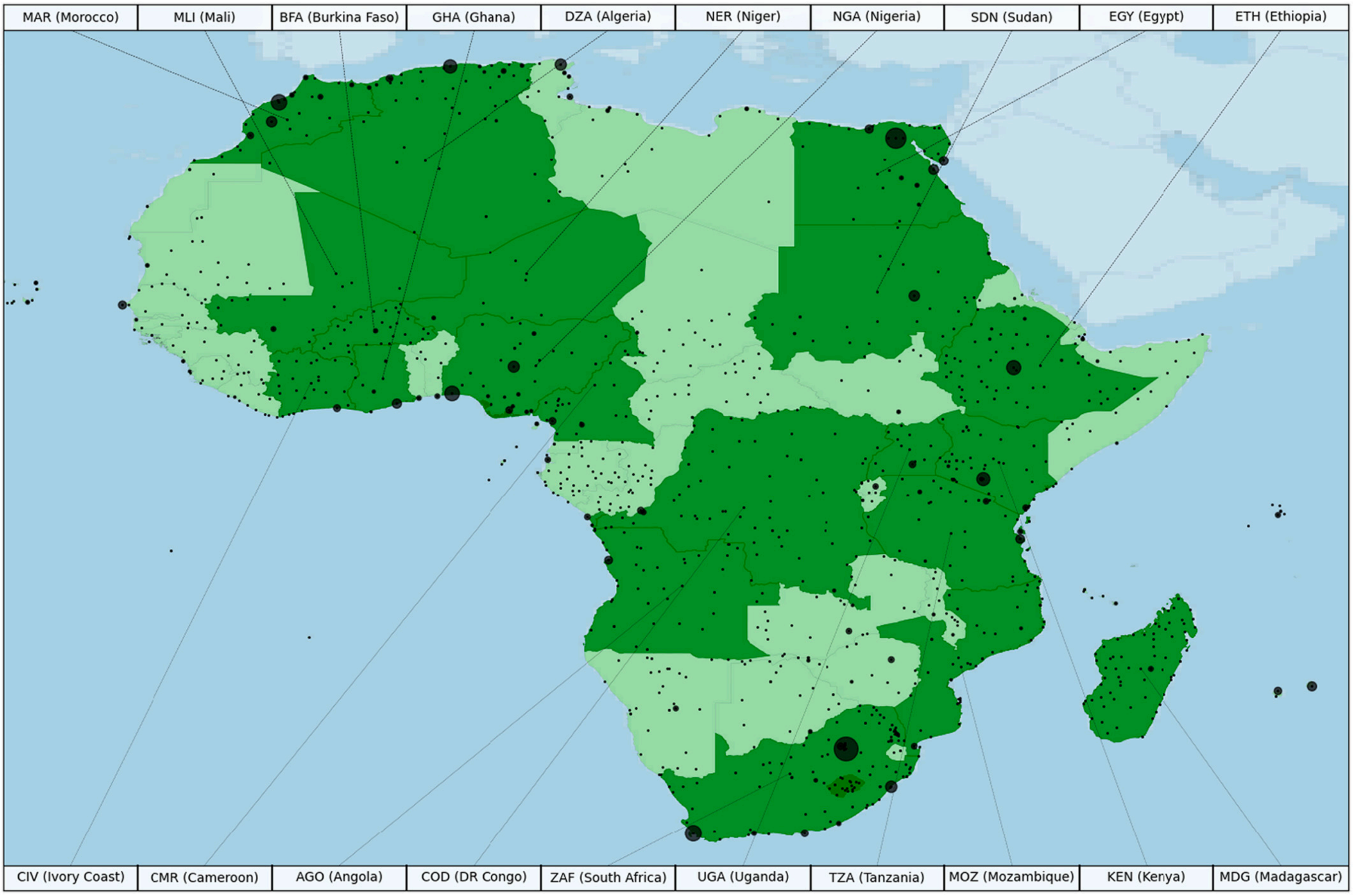

Fig. 2. Visualization of the 20 most populous countries on the African continent (dark green), annotated with their ISO3 country code and name. Black circles represent African airports, their size corresponds to the total number of passengers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the role of Brazilian airlines and cargo airlines, respectively. Iaquinto (2020) discussed the impact of COVID-19 on global tourism and argued that COVID-19 should be taken as an opportunity to rethink mobility.

2.2. Epidemic spreading under air transportation

Several studies have developed and applied epidemic spreading models for the purpose of forecasting and understanding the evolution of COVID-19. For instance, Lau et al. (2020), Christidis and Christodoulou (2020) found that there exists a strong linear correlation between the reported COVID-19 cases inside China and the passenger volumes between distinct domestic regions based on flight data early in the year 2020. Similarly, Hossain et al. (2020) showed that the arrival time of the virus can be predicted rather well by using a compartmental meta-population model on Chinese airports. Several studies performed related experiments on other countries and regions, usually identifying the prominent role of air transportation (Li, Huang, Wang, Yuan, & Peng, 2020; Nikolaou & Dimitriou, 2020; Zhang, Zhang, & Wang, 2020) or the combination of several transportation modes (Li, Rong, & Zhang, 2021; Zhang et al., 2020).

2.3. The role of Africa under COVID-19

A few studies in the recent literature address the evolution and drivers of COVID-19 on the African continent. Bamgboye et al. (2020) analyzed the evolution of reported cases in Africa, identifying significant differences in Africa compared to other continents. Nordling (2020) and Maeda and Nkengasong (2021) formally stated the puzzle of Africa during the COVID-19 pandemic. Diop et al. (2020) hypothesized that the spread of COVID-19 in Africa is significantly slower compared to other parts in the world mainly due to its younger population. Ondoa et al. (2020) assessed the COVID-19 testing strategies on the African continent, as a pillar for its outbreak response, together with a set of further recommendations. Songok (2020) discussed that a limited number of tests leads to underrepresentation of reported COVID-19 cases in Africa. Uyoga et al. (2020) performed a survey on the prevalence of anti-SARS-CoV-2 immunoglubolin G within parts of the Kenyan population, finding that the officially reported cases are possibly by a factor of 30 too small.

To the best of our knowledge, there exists no study in the literature which performs an in-depth analysis on the role of air transportation for the African continent, and how it might have contributed to or hindered the spread. Our study aims to fill this gap in the literature.

3. Epidemiological evolution of COVID-19 in Africa

The epidemiological data in this study was obtained from an open data repository: Coronavirus Source Data from Our World in Data (`https://ourworldindata.org/coronavirus-data`). To provide an overview, Fig. 3 shows the evolution of confirmed COVID-19 cases for selected African countries in the year 2020. For each of the top 20 countries by population, the number of confirmed COVID-19 cases is shown, with countries being stacked on top of each other. By the end of 2020, South Africa (ZAF) was the hardest-hit country (in total confirmed cases), having reported more than one million cases. One possible driver of the devastating impact of COVID-19 on South Africa was the emergence of a mutation, the so-called *South African variant*,

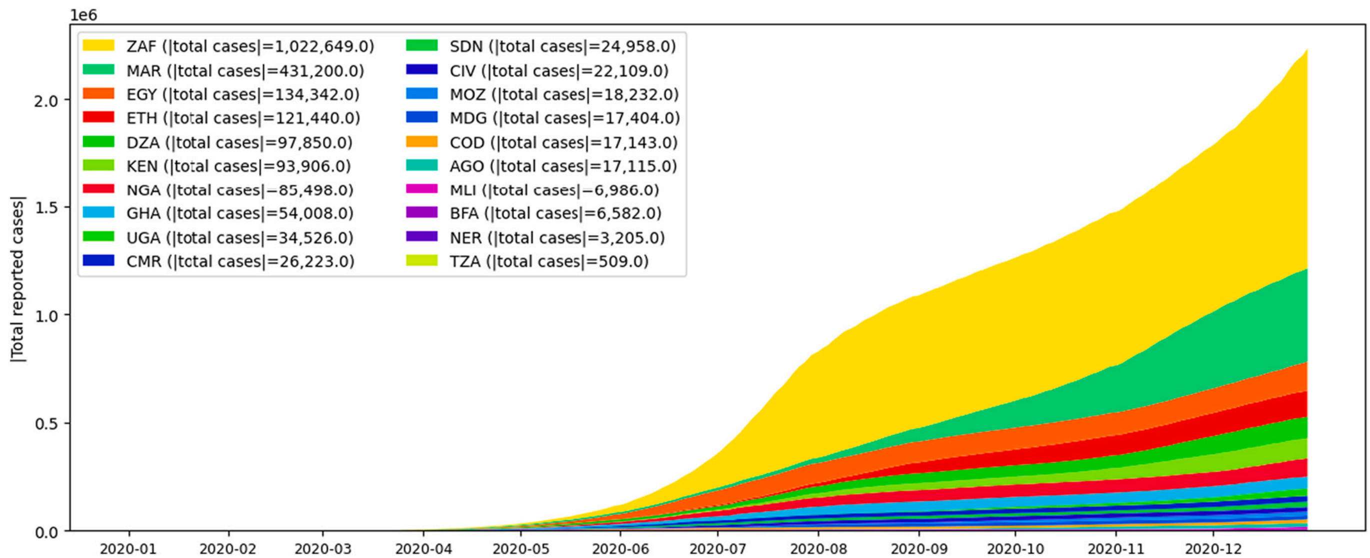

Fig. 3. Evolution of the number of reported cases for the top 20 African countries throughout the year 2020 as a stacked line chart. Countries are ranked vertically by their total number of reported cases.

Lineage B.1.351. While research on such variants of concern is still under progress in the scientific literature, it has been stated that this variant is much easier to transmit and might partially evade vaccination (Singh et al., 2021). To better understand and compare the evolution of individual countries, we visualize the 0/1-normalized number of infections for each of the top 20 African countries against all countries worldwide in Fig. 4. The African countries have hit their exponential growth phase relatively late. Notably, South Africa (ZAF) reached the first peak around July 2020, later than several other heavy-hit countries in the world. Some countries, including Burkina Faso (BFA), Mali (MLI) and Uganda (UGA), were hit particularly late. A few exceptions for countries which reach their peak relatively early include Ivory Coast (CIV), Ghana (GHA), Nigeria (NGA), and Sudan (SDN). Tanzania (TZA) is an exception according to our data with an extremely small number of confirmed cases in the year 2020.

In Fig. 5, we report the pairwise correlation between the evolution of confirmed cases in the top 20 African countries. For each time series of confirmed cases, we compute the Pearson correlation coefficient, which is shown in the upper right of each subplot. Country pairs with coefficients larger than 0.6 are highlighted in red colour. We can see that the evolution of the pandemic in different parts of Africa is a rather heterogeneous process, at least according to the number of confirmed cases, consistent with results in the literature (Bamgboye et al., 2020). A few correlations between countries stand out and are explained as follows. The evolution in Nigeria (NGA) is correlated with Ivory Coast (CIV), DR Congo (COD), Egypt (EGY), and South Africa (ZFA). Especially the correlation coefficient between Nigeria (NGA) and South Africa (ZFA) is rather high (0.83). There could be various reasons for the strong correlation: Both countries have a very large population (see Table 1 in the Appendix) and are rather well connected to non-African countries, which could imply that they receive their initial cases at a similar time. In addition, the two countries could be similar in the implementation of

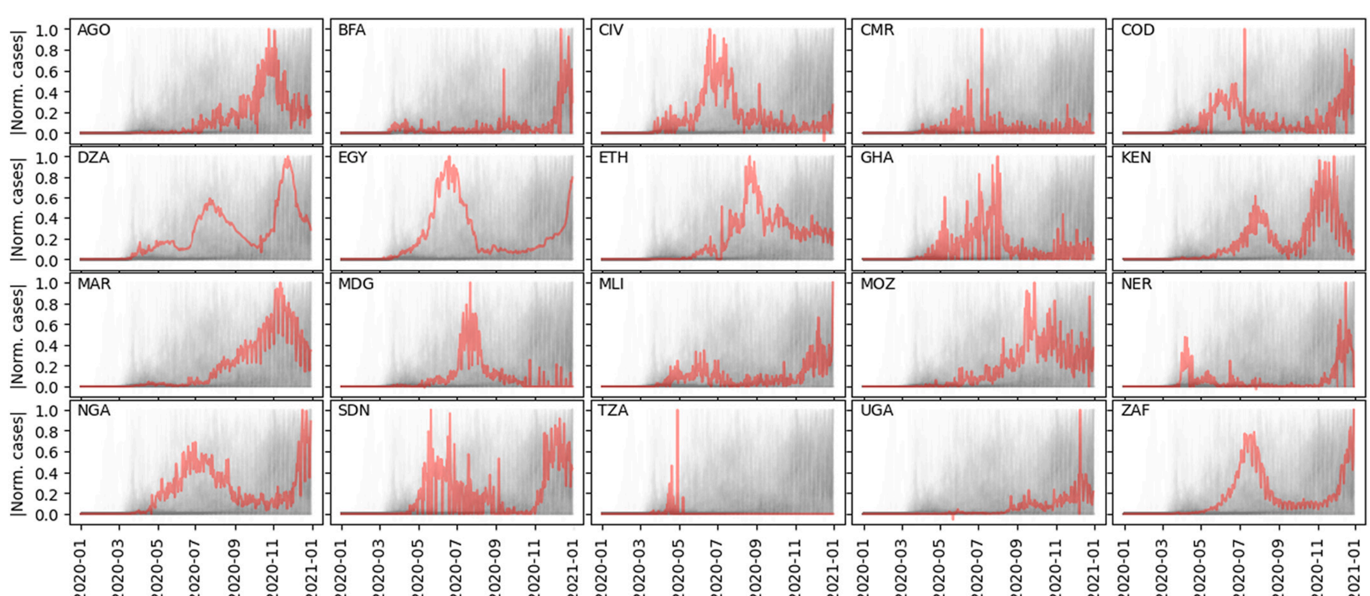

Fig. 4. Normalized number of reported daily cases of the top 20 African countries. The red line visualizes the evolution of the specific country, while the gray, semi-transparent lines visualize the curves for all countries worldwide. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

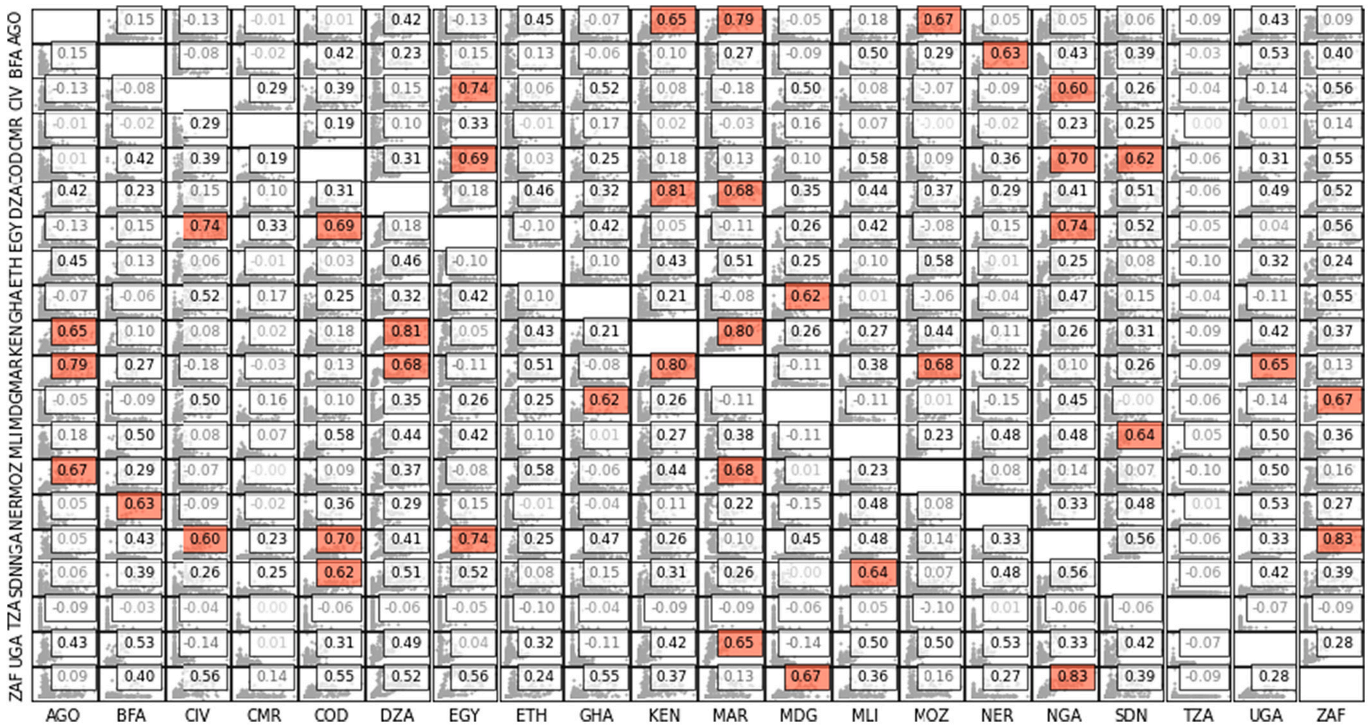

Fig. 5. Correlation of the daily reported number of confirmed cases between the top 20 African countries. Higher values and darker cells indicate stronger positive correlation. Correlations stronger than 0.6 are highlighted.

testing strategies. Finally, there could be other, unobservable similarities in societal behaviors between the two countries. A second group of highly-correlated countries consists of Angola (AGO), Kenya (KEN), Morocco (MAR), and Mozambique (MOZ). Again, we have two African countries which are rather well connected internationally, i.e., Kenya (KEN) and Morocco (MAR), which play a key role as continental hubs inside Africa. For most remaining African country pairs, we cannot observe a significant correlation between the number of confirmed cases, which could either indicate a heterogeneous spread or significant differences in the implementation of testing strategies. Overall, the situation in Africa is heterogeneous and the number of confirmed cases is significantly lower than those expected by many experts in the beginning of the pandemic. We have performed additional experiments with the Spearman rank correlation coefficient, replacing the Pearson correlation coefficient, the results do not reveal significant different differences.

4. Air transportation evolution in Africa

Africa has long been regarded as aviation's last frontier (Lubbe & Shornikova, 2017; Pirie, 2016). While the academic research on African air transport is relatively rare as compared to that on other continents, the literature is growing; see, e.g., Abate (2016), Abate and Kincaid (2018), Njoya (2016), Martini and Scotti (2017), Warnock-Smith and Njoya (2017). We complement this literature by focusing on the evolution of the inter- and intra-African flights during the COVID-19 pandemic.

The flight data was obtained from Flightradar24 (`https://www.flightradar24.com`). We begin with the intra-continental connectivity, i.e., connections inside Africa. Fig. 6 shows the direct flight network among African countries based on data for the year 2019 (pre-COVID-19). We reuse the notion of country networks as presented in earlier research by Wandelt and Sun (2015), which performs a data aggregation step to better understand the inter-country transportation system, without showing the domestic flows explicitly. In such a country network, nodes represent individual countries and links represent flights between any two airports between these two countries. The number of flights on a link in the country network equals to the sum of flights along all airport pairs between the pair of countries.

The width of links between countries in Fig. 6 represents the bilateral air transportation activity pre-COVID-19. The top 20 countries are annotated with the ISO3 country codes. A few countries stand out in terms of enabling efficient air transportation inside Africa. Specifically, several countries along the coastline seem to act as bridges for connecting their neighborhood. These countries include South Africa (ZAF), Morocco (MAR), Kenya (KEN), Nigeria (NGA), and Ivory Coast (CIV). Strikingly, many of these countries were identified as highly correlated regarding the COVID-19 evolution in the previous section. Accordingly, we can conclude that air transportation could indeed play a critical role for the spread of COVID-19 in Africa as well. Ethiopia (ETH) seems like a special case here: Despite its central role for African air transportation, its number of confirmed cases was not highly correlated with other countries. African countries whose air transportation volume and degree of connectivity is much lower, were less synchronized and rather developed their own epidemiological characteristics. Nevertheless, it should be emphasized again that air transportation is only one of the drivers; there are many others, including ground transportation, health-care development status, and climate. A specific quantification of the contributions for these individual factors is a very important direction for future work. Yet, the observation about the synchronization of confirmed cases among these key air transportation hub countries in the year 2019 is interesting on its own.

The above analysis considered the air transportation system pre-COVID-19 in Africa. Next, we investigate the evolution of air transportation throughout the year 2020. For this purpose, we extracted a total of twelve monthly country networks for 2020. The results are shown in Fig. 7. For the first two months of 2020, the network is highly similar with the network derived for 2019. Starting from March 2020, we can observe initial changes, which mostly consist of flow reductions in the Northern parts of Africa. Particularly, we can see that Morocco (MAR) and Tunisia (TUN) reduced their intra-continental flights. This is somewhat consistent with what has been found in early research on

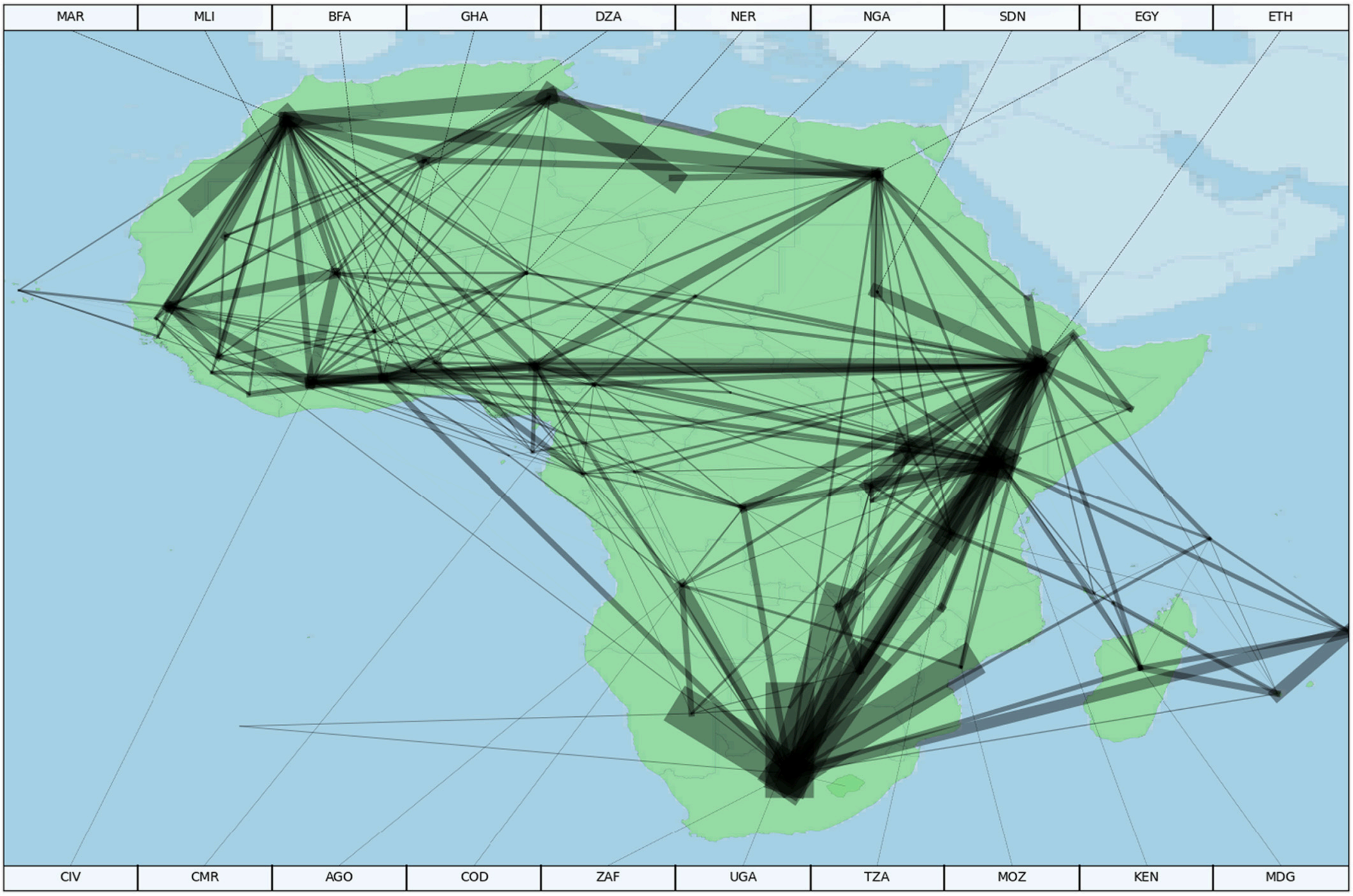

Fig. 6. Situation of the African air transportation network before COVID-19. The thickness of a link corresponds to the total number of flights between a pair of countries. The top 20 African countries are labeled with the ISO-3 country code.

other parts of the world, where the major flight restrictions in Europe took place in the middle of March 2020 (Sun, Wandelt, & Zhang, 2021b). Several other African countries, including South Africa (ZAF), on the other hand, show a less significant reduction in connectivity and flow magnitude, indicating that in March 2020 it was still well-connected in the Southern part of the African continent. This means, that the disease still had ample opportunity to spread. Starting with April 2020, we can see that almost all inner-African flights collapsed; a recovery gradually started in July/August 2020. By the end of 2020, the connectivity of the country network is largely recovered, but the flows are smaller compared to the first two months of 2020.

For the next experiments, we have extracted the daily country network of the African continent, consisting of 54 countries. In total, we have 731 snapshots for the years 2019 and 2020. In order to investigate the temporal evolution of the networks, we have computed nine frequently-used global network properties from the network science domain. Fig. 8 reports the evolution, with the period between March 2020 and September 2020 showing significant perturbations to the overall system. The results specific to that period can be summarized as follows (where N is the set of nodes, $n = |N|$, and m is the number of links):

1. **Assortativity:** The assortativity coefficient (Newman, 2002) is significantly negative, which indicates that in the networks high-degree nodes preferably connect to low-degree nodes.
2. **Average shortest path length (ASPL):** The average shortest path length is increased from 2.1 to around 4.0, indicating that a random traveler needs on average two more hops to reach the destination.
3. **Cycle basis:** The minimal cycle basis in the network is smaller, indicating a significantly reduced redundancy.
4. **Density:** The density is slightly increased, being caused by the significantly reduced number of nodes (see below).
5. **Diameter:** The length of the longest shortest path in the network is increased from five to ten.
6. **|Links|:** The total number of links m is reduced by almost 90% in March 2020 and slightly started to recover in July 2020.
7. **|Nodes|:** The number of nodes n shows a similar behavior as the number of links.
8. **Percentage of periphery nodes:** The ratio of the number of periphery nodes (with eccentricity equal to the diameter) reveals a slight increase in the highlighted period.
9. **Transitivity:** The transitivity undergoes some perturbations, mainly induced by the significant reduction in the number of links.

In the next experiment, we turn from the analysis of global network properties to node properties. Two highly relevant node importance metrics for air transportation are degree and betweenness. The degree of a node counts the number of direct neighbors, i.e., airports which can be reached by a direct flight. The betweenness of a node indicates the number of shortest paths a node appears on, estimating the frequency a random traveler would have to pass through a given country. It is known that a high node degree does not necessarily coincide with high betweenness in air transportation (Guimera, Mossa, Turtschi, & Amaral, 2005); accordingly, both notions contribute to the function of hubs: the degree directly and the betweenness indirectly. Fig. 9 reports the evolution of the top ten African countries ranked by the product of the two metrics. Please note that looking at betweenness alone will reveal so-

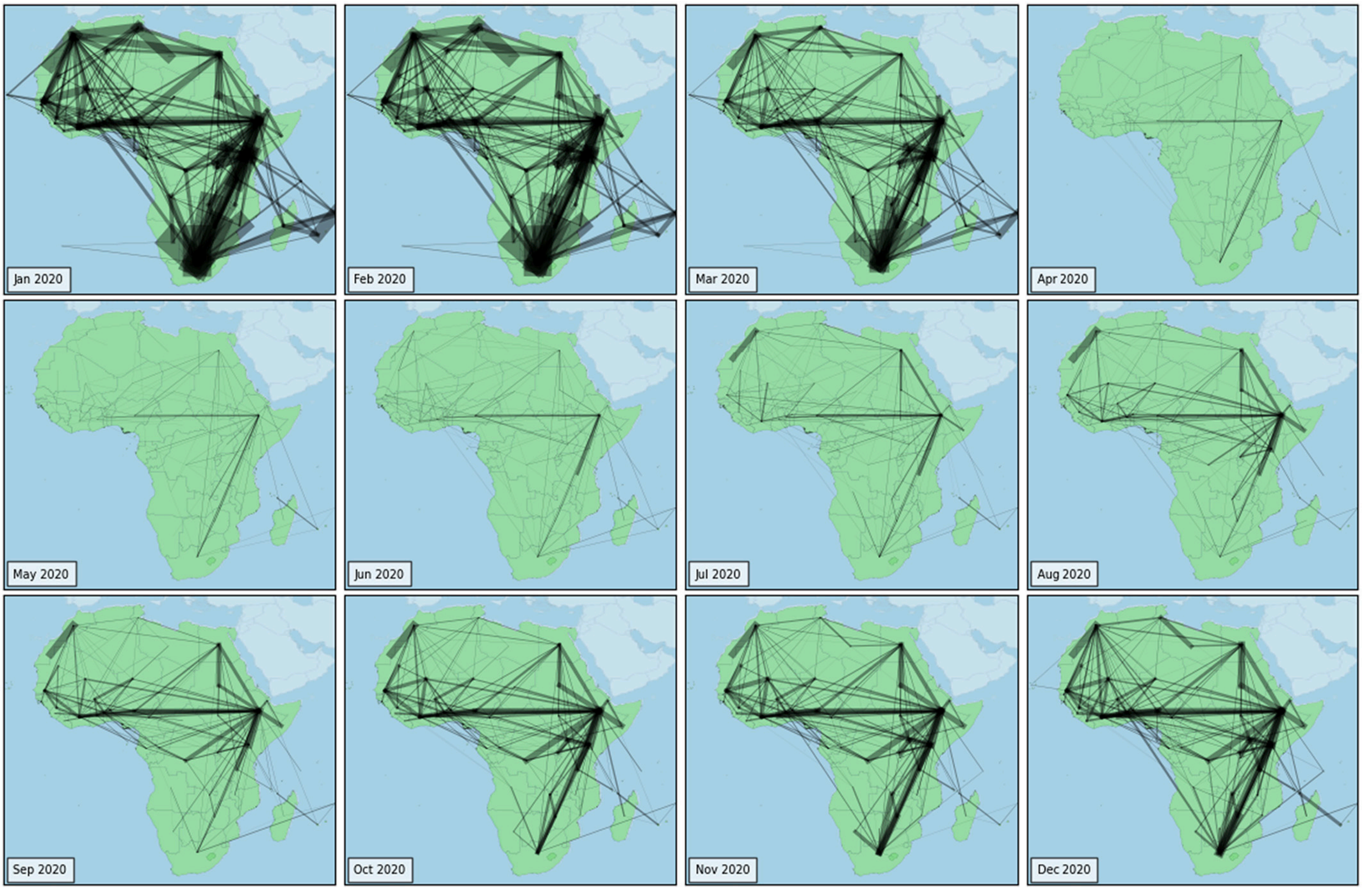

Fig. 7. Evolution of the inner-African flights during COVID-19. Each subplot corresponds to the country network at a given month in 2020.

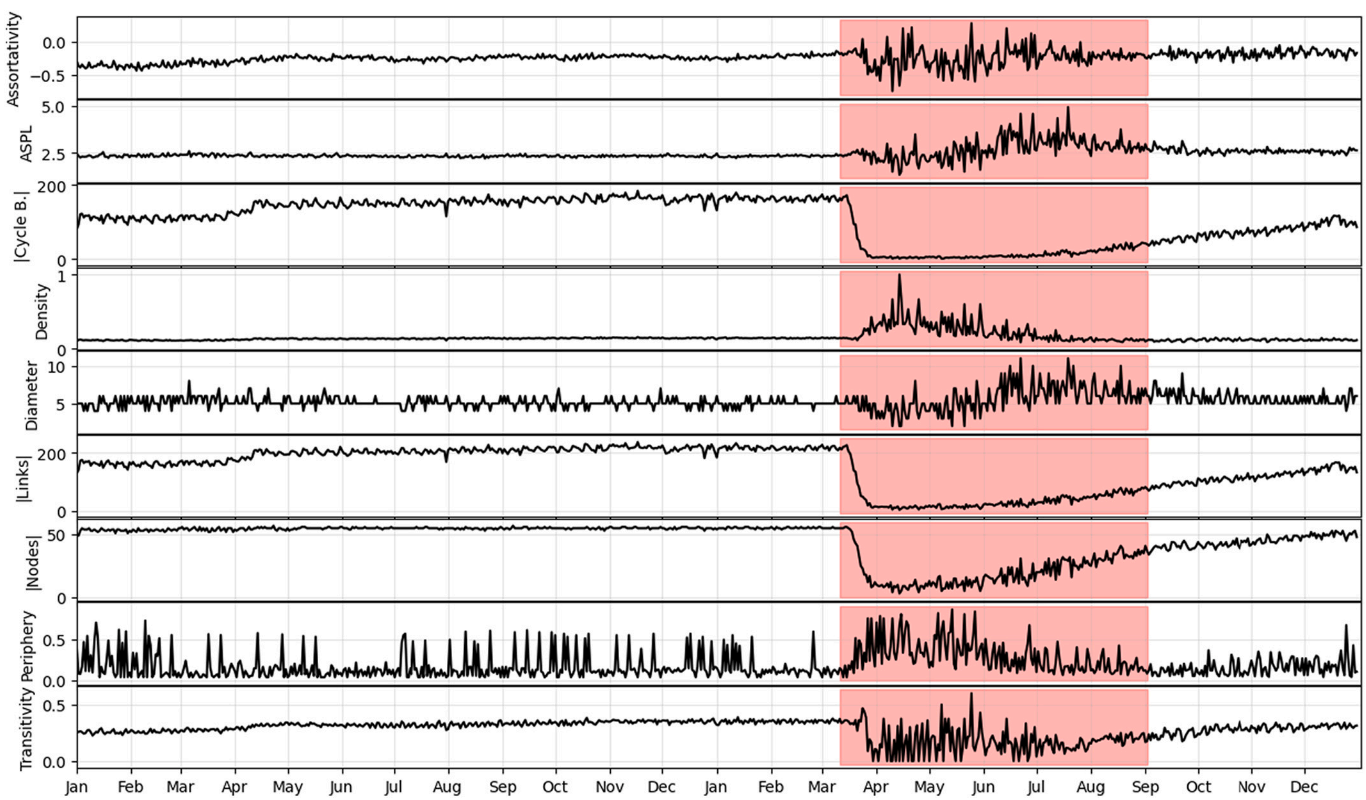

Fig. 8. Evolution of nine selected network metrics for the inner-African country network in the years 2019 and 2020.

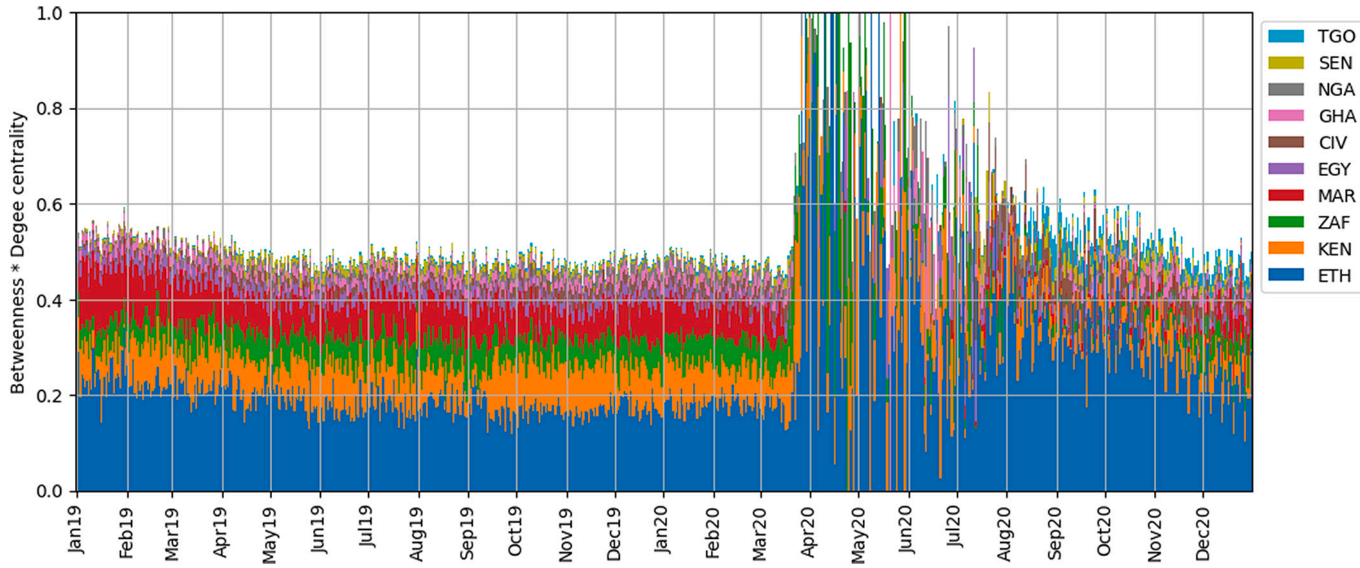

Fig. 9. Evolution of the node importance of the overall top 10 highest ranked countries according to the product of node degree and betweenness.

called anomalous nodes only (Guimera et al., 2005); accordingly, we report the product of both metrics here.

Below, we describe the temporal evolution of the flights for three selected countries in detail: Ethiopia (ETH), Kenya (KEN), and South Africa (ZAF). These three countries have a high topological importance (Sun, Wandelt, & Zanin, 2017) in the African air transportation system, as shown in our experiments on node statistics above, i.e., these three countries are top-ranked in Fig. 9. For each of the three countries, we visualize the connectivity to their highly-connected neighbors in Fig. 10, Fig. 11, and Fig. 12. For each sub-chart, the evolution of the max-normalized flights throughout the year 2020 is shown. We make a set of interesting observations based on these visualizations. First, the flight reduction by Kenya (KEN) and South Africa (ZAF) are much stronger than those implemented by Ethiopia (ETH). The latter country has implemented flight bans mainly for a period of 3–6 months; the length of the period is destination country-specific. For instance, the connection between Ethiopia (ETH) and Egypt (EGY) was disrupted for a period of three months and quickly recovered to more than 60% of its original capacity. The connection between Ethiopia (ETH) and Uganda (UGA), on the other hand, has been disrupted for more than half a year. This is an interesting observation, since Uganda (UGA) had a much better path throughout the COVID-19 pandemic in the year 2020, compared to Egypt (EGY). In fact, the flight recovery between Ethiopia (ETH) and Egypt (EGY) coincides with the peak of confirmed cases in Egypt (see Fig. 5 above). And, notably, the number of confirmed cases in Ethiopia (ETH) went up significantly a few weeks after reopening travel with Egypt (EGY). This indicates that half-hearted, temporary flight bans are not a solution towards handling a pandemic.

Kenya (KEN) reveals a very heterogeneous behavior under the pandemic in 2020, as shown in Fig. 11. Some of the connections have not seen recovery until the end of 2020, e.g., Madagascar (MDG) and Sudan (SDN). Other connections have been recovered towards the fourth quarter of 2020, including Ethiopia (ETH) and Ghana (GHA). It is interesting to note that Kenya just hit its second wave of cases in the fourth quarter of the year 2020; indicating a relationship with the flight recovery as well. Finally, the evolution for South Africa (ZAF) is shown in Fig. 12, revealing very strict flight bans to most African countries. Nevertheless, three countries stand out, in terms of early recovery: Kenya (KEN), Ethiopia (KEN), and Egypt (EGY). It is plausible to argue that the early recovery of these connections partially spurred the devastating outbreak of COVID-19 in South Africa (ZAF) towards July/ August 2020.

The next experiment in this section concerns the international connectivity of the African continent. Here, we build a continental network, where nodes are continents and the weight of links represent the daily number of flights among continents. The results are shown in Fig. 13. We

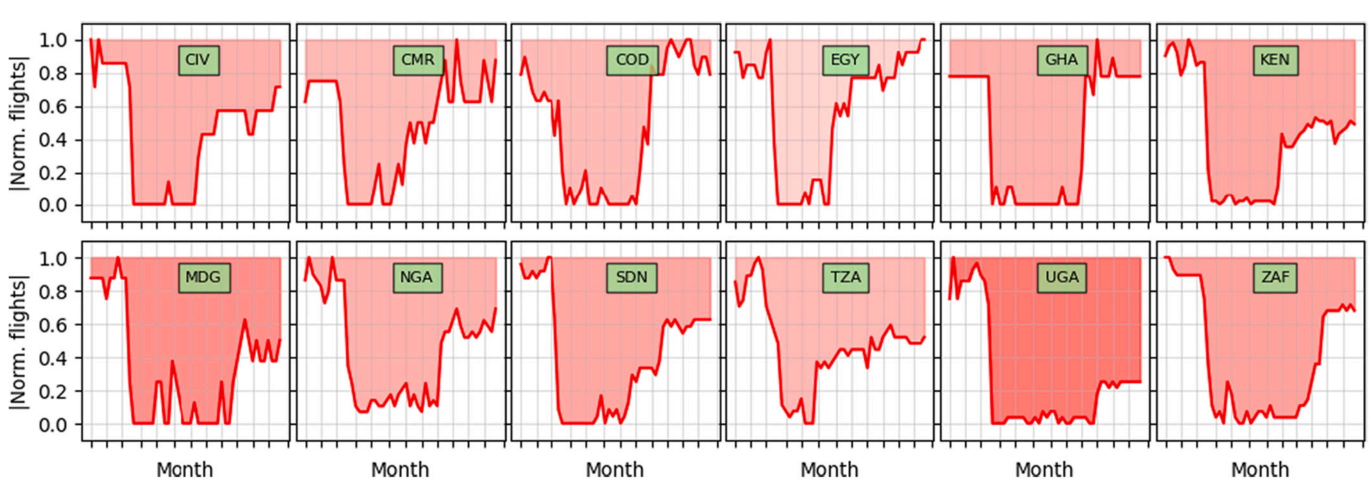

Fig. 10. Temporal evolution of the normalized number of flights between Ethiopia (ETH) and twelve highly-connected neighbors.

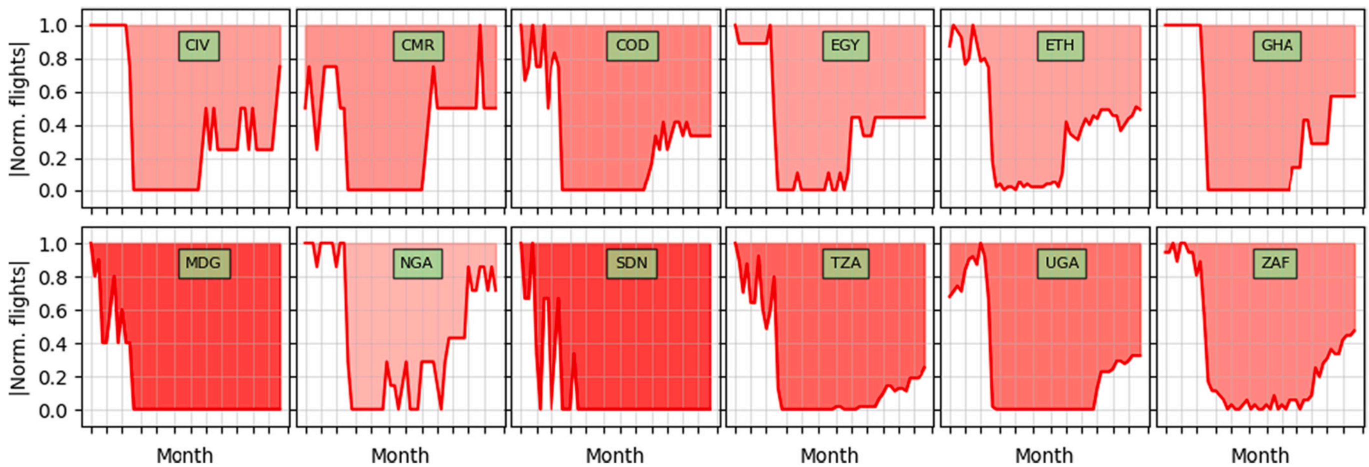

Fig. 11. Temporal evolution of the normalized number of flights between Kenya (KEN) and twelve highly-connected neighbors.

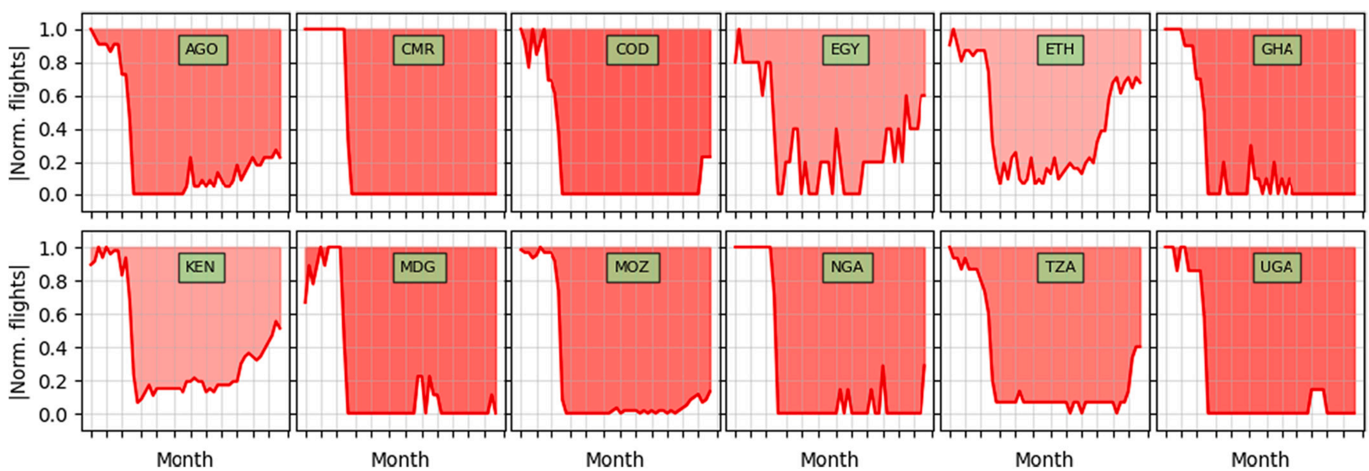

Fig. 12. Temporal evolution of the normalized number of flights between South Africa (ZAF) and twelve highly-connected neighbors.

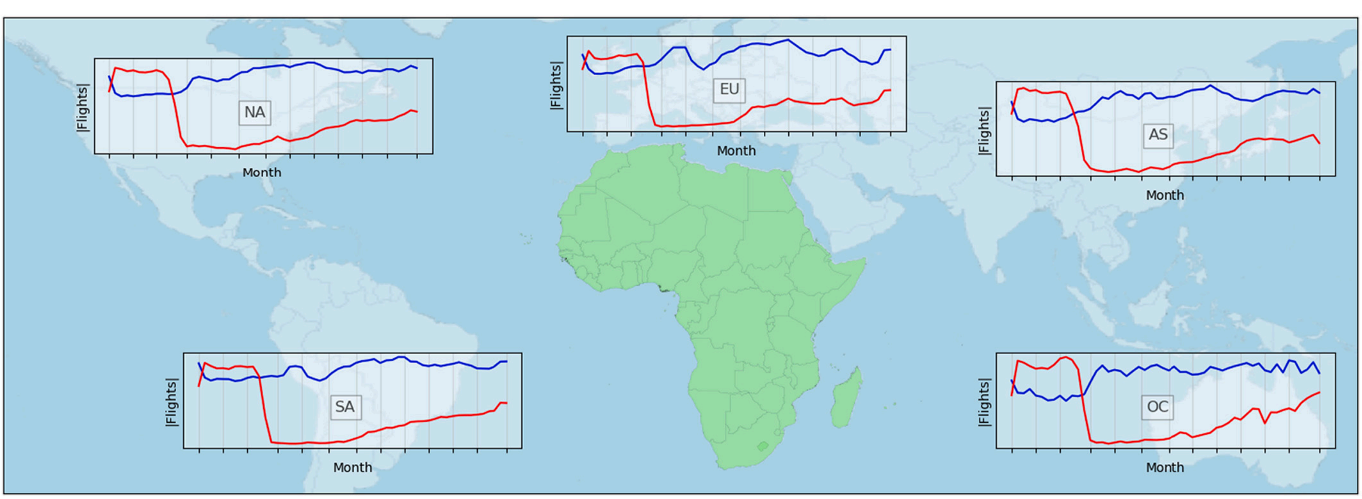

Fig. 13. Evolution of the inter-continental flight connectivity between Africa and other continents. For each continent two curves are reported: The blue curve corresponds to the weekly number of flights in the year 2019 and the red curve corresponds to the ones in the year 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

find that the number of inter-continental flights with Africa was significantly reduced in March 2020. This reduction seemed to have happened in a synchronized way towards all other continents. Interestingly, the magnitude of flights did almost reach zero, meaning that the African continent was largely disconnected from other parts of the world in the period between April 2020 and June 2020. Starting from July 2020, the air transportation activity started to slowly recover. Similar to the flight bans, the degree of recovery is rather synchronized among all continents; flights towards Oceania are perhaps recovering slightly faster than those flights to other continents, particularly towards the end of 2020. The recovery towards Europe was stalled in the period between September 2020 and November 2020, possibly because of multiple strong outbreaks on the European continent in Summer 2020.

Fig. 14 extends the earlier results and shows the evolution of airports and their spatial locations in Africa. We find that most airports along the North coast and South coast were significantly affected by the pandemic, large airports and small airports alike. In the inner parts of Africa, mainly around the equator, we can find that some airports did not incur such strict flight bans. While these are mainly smaller airports, it is a striking observation. Specifically, this means that from these smaller airports, there is an unreduced potential to spread the virus. The reasons for virtually non-existent flight reductions in this area are not clear. One possible explanation could be a lack of control measures and containment policies in the concerned countries.

Fig. 15 provides a comparison of the evolution for the international flights (blue) and the number of confirmed COVID-19 cases (red). The data is 0/1 normalized to compare both indicators and to perform cross-country comparisons. This chart aims to explore the possible degree of synchronization between the two indicators. We can distinguish two larger groups of countries, as discussed below.

The first group consists of countries where the number of infections increases soon after the number of international flights was reduced. This group includes, for instance, Ivory Coast (CIV), Algeria (DZA), Egypt (EGY), Ghana (GHA), Mali (MLI), Niger (NER), Nigeria (NGA), and Tanzania (TZA). For these countries, flight reductions possibly came too late. Particularly, it should be noted that there is an unavoidable delay between the implementation of flight reductions and measurable results for multiple reasons. First, from an infection to the confirmation, it might take up to two weeks. Second, there are possibly undetected cases in the population. An increase in the number of confirmed cases should not be misinterpreted as the first event of infections taking place. Accordingly, we think that the flight restrictions for countries in the first group very likely came too late. And although the continent locked itself up quite strictly concerning inter-continental flights, the disease had a sufficiently-large time window to enter the continent and start to spread locally.

For the second group of countries, there is a visible delay between the flight reductions and emergence of confirmed cases, i.e., the number of confirmed cases increases significantly only months after flight bans have been introduced. This group includes Angola (AGO), Burkina Faso (BFA), Kenya (KEN), Mozambique (MOZ), Uganda (UGA), and South Africa (ZAF). In this context, it is noteworthy that Kenya was shown to had a high potential for under-reporting of confirmed cases (Uyoga et al., 2020), which indicates that the number of infections had increased much earlier than the officially confirmed cases. Finally, Ethiopia (ETH) takes an interesting role here, given that its international flight reductions were not as strong as those for other countries. The incoming passenger flow - despite being reduced in magnitude - left

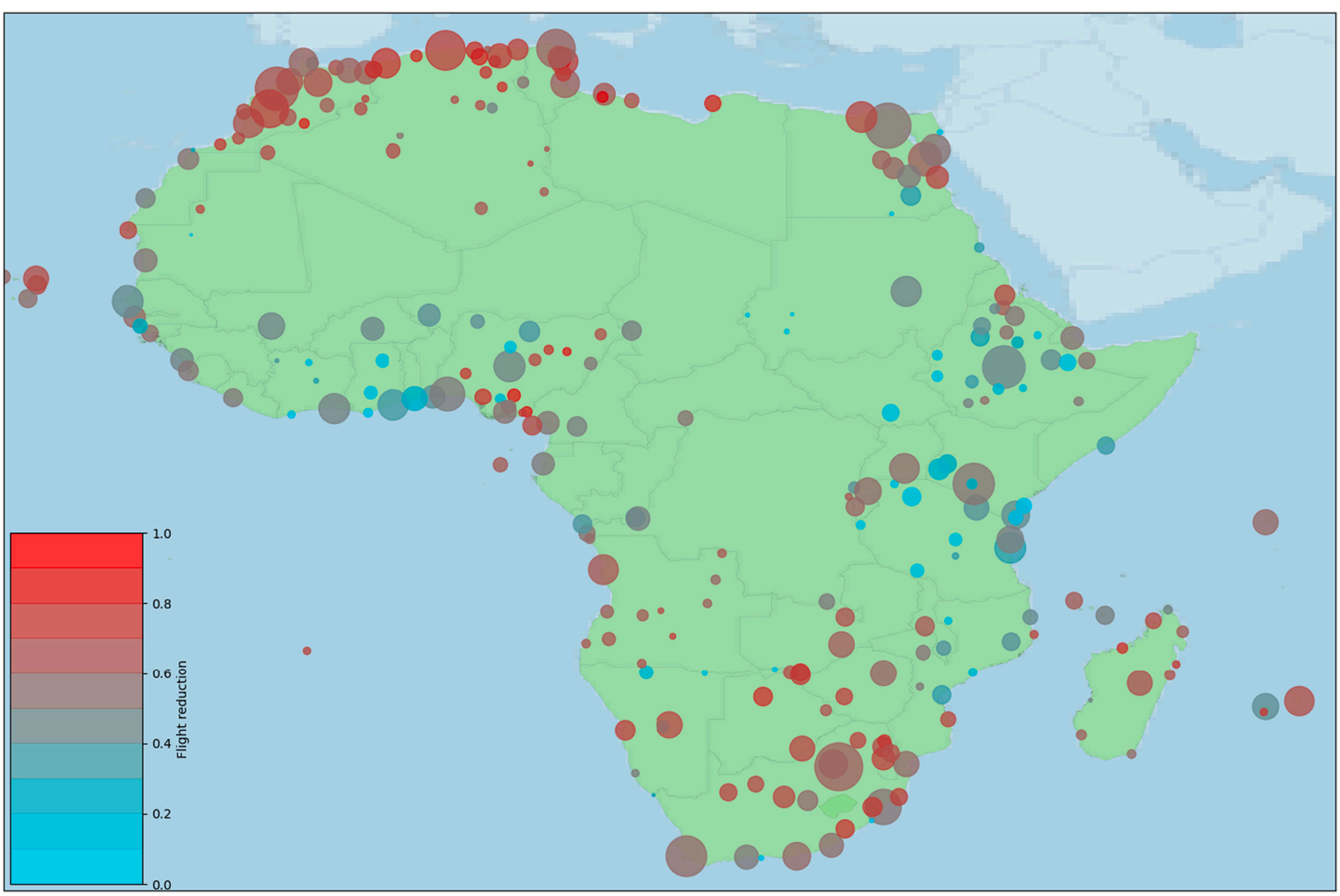

Fig. 14. Changes in airport connectivity throughout the year 2020. Larger values (dark red) represent stronger reduction of flights from an airport. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

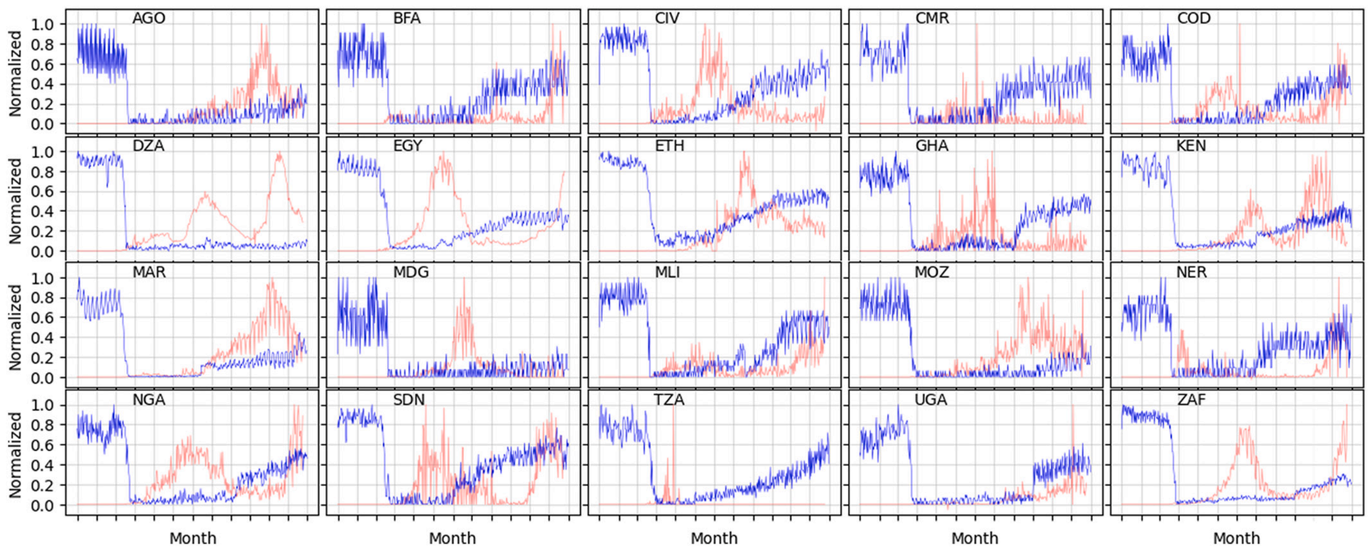

Fig. 15. Normalized international flights (blue) versus normalized number of confirmed cases (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

enough room for importing the disease. Another important observation regarding Ethiopia (ETH) is its flight recovery inside Africa matches exactly the time of entering Ethiopia's exponential growth phase in the number of confirmed COVID-19 cases; refer back to Fig. 7, where Ethiopia (ETH) took a leading role in July 2020 and August 2020 concerning the inner-African air transportation. It is possible that the reopening of inner-African flights event was a dooming factor for the African continent and the evolution of COVID-19.

5. Conclusions

This study has performed an in-depth analysis of the role air transportation had on the African continent throughout the evolution of the COVID-19 pandemic. This is to the best of our knowledge the first study aiming to explain the evolution of COVID-19 cases in Africa by using real air transportation data for the year 2020. Given that the performance of Africa in this pandemic is considered a major puzzle in the literature, we hope that our study contributes to a better understanding of its disease dynamics. Below, we summarize the major findings of this study and provide a set of recommendations for future work.

5.1. Major findings and policy implications

Our study, mainly based on flight and epidemiological data for the years 2019 and 2020, has led to several major findings. Most importantly, our analysis has shown that air transportation could have indeed played a critical role in the spread of COVID-19 in Africa. This fact has been reported for other countries and continents in the literature, but, to the best of our knowledge, not on Africa. Particularly, we find that several African countries with highly-correlated confirmed COVID-19 cases take central positions in the African air transportation system. These countries include South Africa (ZAF), Morocco (MAR), Kenya (KEN), Nigeria (NGA), and Ivory Coast (CIV). A high synchronization of confirmed cases suggests strong interactions between the populations: Well-established air transportation can be one such explanation for strong interactions. Accordingly, we recommend that studies which aim to understand and resolve the puzzle of COVID-19 on the African continent, do need to consider air transportation. It might be tempting to neglect air transportation for analysis on Africa, as Africa is a largely developing continent, but, epidemiologically, air transportation is the major driver of long-distance spreading.

Second, we identified a heterogeneous response of African countries in terms of international flight restrictions and the evolution of confirmed COVID-19 cases. For several African countries we conclude that the flight restrictions came too late; a finding like what has been reported in Europe and the United States in the literature. It should be reiterated that air transportation is mainly an initial driver of disease spreading. From an epidemiological point of view, a single unobserved infection on a continent is - in theory - sufficient to turn into a continental outbreak. Accordingly, the delayed intra/inter-continental flight reduction of a single African country can lead to severe consequences for the whole continent, since the virus can spread by intra-continental flights and through ground transportation. There is a need for orchestrated responses in face of an epidemic outbreak threatening to turn into a pandemic. It is a dangerous misbelief that partial flight bans towards selected source countries helps in the fight against a pandemic. History has repeatedly shown that passengers are willing to accept (complex) rerouting in order to reach their destinations; and the highly-redundant air transportation system provides ample opportunity for passengers to circumvent country pair-specific flight bans.

Third, the importance and role of individual countries in this pandemic should be investigated in future work. As we have shown in this study, Ethiopia (ETH) obtained an outstanding role of importance from the complex network perspective throughout the period between March 2020 and June 2020. Such a tremendous shift in node importance is accompanied by a significant shift in network dynamics, particularly regarding simulations for disease spreading. A node with higher degree and betweenness is significantly more likely to be an active hub for disease spreading. Therefore, models for pandemic forecasting and explanation should always rely on the latest data. As an example, taking flight data for the year 2019 for simulating the spread in the late stages of 2020 will be highly misleading, as the flow of passengers and importance of airports has undergone tremendous changes throughout one year. A model with inaccurate (outdated) input data will necessarily lead to the wrong conclusions.

Fourth, our experiments on actual flight data alone do not lead to a definite answer towards the puzzle of COVID-19 on the African continent. We can partially observe arguments for the most plausible explanations. On one hand, it could well be the African continent was saved from a worse epidemiological situation based on more restrictive flight bans, compared to European countries and the United States. On the other hand, a significant underreporting of cases could also explain the delay of confirmed COVID-19 cases compared to the implemented flight restrictions in some African countries. Overall, it can be concluded that there is an outstanding need for more studies on this special continent, with a better focus on obtaining reliable data. Uyoga et al. (2020) was a first important step into that direction, but there is an urgent need to further studies, particularly at a larger scale.

5.2. Limitations and future work

The drivers behind the evolution of COVID-19 in the African continent are manifold and heterogeneous. Our study sheds some light from the perspective of air transportation. A possible direction for future work would be an extension with the consideration of ground transportation data, which could complement our analysis presented here. Air transportation is most important for the initial importation of a disease. Once the virus has infected a sufficiently large subpopulation, the remaining disease dynamics mainly depend on other transmission media and parameters, e.g., public transit, social distancing, and application of facial-masks policies. An investigation of such factors requires much more detailed data but will also lead to realistic and fine-grained insights into the process of epidemic spreading. Moreover, it would be interesting, yet challenging, to implement a simulation framework, which allows to model interactions among different factors (not only concerning transportation, but also age groups and health case development status) and assess their impact. Furthermore, it would be interesting and important to use more recent data to explore how Africa performs with respect to the new variants of concern relative to the rest of the world (e.g., Sun, Wandelt, and Zhang (2021a)) and the factors that influence the performance. Finally, the analysis in our study is based on flights (aircraft movements) data; as all data-driven research, our results depend on and change with the availability and quality of additional data. Given the lack of actual passenger trajectories, we have used the number of flights between countries as a connectivity indicator. This should be understood as a proxy, as it neglects the load factor of aircraft as well as the transformation of passenger aircraft to cargo aircraft throughout the pandemic. Future research could analyze actual passenger data once such data becomes available. Based on such data, one could perform experiments on behind/beyond traffic, further pushing the envelope or understanding micro-dynamics underlying COVID-19 and African aviation.

Author statement

Xiaoqian Sun: Conceptualization, Methodology, Writing - Original draft preparation. **Sebastian Wandelt**: Conceptualization, Writing - Reviewing & Editing. **Anming Zhang**: Conceptualization, Validation, Writing - Reviewing and Editing.

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Appendix A. Appendix

Table 1
List of African countries with country code in the experiments.

ISO3	Name	Subregion	Capital	Population	Area	Airports
NGA	Nigeria	Western Africa	Abuja	195,874,740	923,768	26
ETH	Ethiopia	Eastern Africa	Addis Ababa	109,224,559	1,104,300	49
EGY	Egypt	Northern Africa	Cairo	98,423,595	1,002,450	28
COD	DR Congo	Middle Africa	Kinshasa	84,068,091	2,344,858	61
ZAF	South Africa	Southern Africa	Pretoria,Cape Town	57,779,622	1,221,037	91
TZA	Tanzania	Eastern Africa	Dodoma	56,318,348	945,087	31
KEN	Kenya	Eastern Africa	Nairobi	51,393,010	580,367	43
UGA	Uganda	Eastern Africa	Kampala	42,723,139	241,550	12
DZA	Algeria	Northern Africa	Algiers	42,228,429	2,381,741	43
SDN	Sudan	Northern Africa	Khartoum	41,801,533	1,886,068	25
MAR	Morocco	Northern Africa	Rabat	36,029,138	446,550	25
AGO	Angola	Middle Africa	Luanda	30,809,762	1,246,700	40
GHA	Ghana	Western Africa	Accra	29,767,108	238,533	5
MOZ	Mozambique	Eastern Africa	Maputo	29,495,962	801,590	37
MDG	Madagascar	Eastern Africa	Antananarivo	26,262,368	587,041	64
CMR	Cameroon	Middle Africa	Yaoundé	25,216,237	475,442	20
CIV	Ivory Coast	Western Africa	Yamoussoukro	25,069,229	322,463	24
NER	Niger	Western Africa	Niamey	22,442,948	1,267,000	6
BFA	Burkina Faso	Western Africa	Ouagadougou	19,751,535	272,967	27
MLI	Mali	Western Africa	Bamako	19,077,690	1,240,192	12
MWI	Malawi	Eastern Africa	Lilongwe	18,143,315	118,484	13
ZMB	Zambia	Eastern Africa	Lusaka	17,351,822	752,612	22
SEN	Senegal	Western Africa	Dakar	15,854,360	196,722	15
TCD	Chad	Middle Africa	N'Djamena	15,477,751	1,284,000	19
SOM	Somalia	Eastern Africa	Mogadishu	15,008,154	637,657	22
ZWE	Zimbabwe	Eastern Africa	Harare	14,439,018	390,757	13
GIN	Guinea	Western Africa	Conakry	12,414,318	245,857	11
RWA	Rwanda	Eastern Africa	Kigali	12,301,939	26,338	5
TUN	Tunisia	Northern Africa	Tunis	11,565,204	163,610	10
BEN	Benin	Western Africa	Porto-Novo	11,485,048	112,622	6
BDI	Burundi	Eastern Africa	Bujumbura	11,175,378	27,834	3
SSD	South Sudan	Middle Africa	Juba	10,975,920	619,745	6
TGO	Togo	Western Africa	Lomé	7,889,094	56,785	2
SLE	Sierra Leone	Western Africa	Freetown	7,650,154	71,740	8
LBY	Libya	Northern Africa	Tripoli	6,678,567	1,759,540	18
COG	Republic of the Congo	Middle Africa	Brazzaville	5,244,363	342,000	25
LBR	Liberia	Western Africa	Monrovia	4,818,977	111,369	14
CAF	Central African Republic	Middle Africa	Bangui	4,666,377	622,984	23

(*continued on next page*)

Table 1 (*continued*)

ISO3	Name	Subregion	Capital	Population	Area	Airports
MRT	Mauritania	Western Africa	Nouakchott	4,403,319	1,030,700	19
ERI	Eritrea	Eastern Africa	Asmara	3,213,972	117,600	4
NAM	Namibia	Southern Africa	Windhoek	2,448,255	825,615	31
GMB	Gambia	Western Africa	Banjul	2,280,102	10,689	1
BWA	Botswana	Southern Africa	Gaborone	2,254,126	582,000	17
GAB	Gabon	Middle Africa	Libreville	2,119,275	267,668	33
LSO	Lesotho	Southern Africa	Maseru	2,108,132	30,355	16
GNB	Guinea-Bissau	Western Africa	Bissau	1,874,309	36,125	2
GNQ	Equatorial Guinea	Middle Africa	Malabo	1,308,974	28,051	6
MUS	Mauritius	Eastern Africa	Port Louis	1,265,303	2040	2
SWZ	Eswatini	Southern Africa	Lobamba	1,136,191	17,364	2
DJI	Djibouti	Eastern Africa	Djibouti	958,920	23,200	5
COM	Comoros	Eastern Africa	Moroni	832,322	1862	4
CPV	Cape Verde	Western Africa	Praia	543,767	4033	10
STP	São Tomé and Príncipe	Middle Africa	São Tomé	211,028	964	3
SYC	Seychelles	Eastern Africa	Victoria	96,762	452	6

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