The heterogeneous severity of COVID-19 in African countries: A modeling approach

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Abstract

Background: The COVID-19 pandemic has had a considerable impact on global health and economics. The impact in African countries has not been investigated through fitting epidemic models to the reported COVID-19 deaths.

Method: We downloaded data for the twelve most affected countries with the highest cumulative COVID-19 deaths to estimate the time-varying basic reproductive number ($R_0(t)$) and infection attack rate (IAR). We developed a simple epidemic model and fitted the model to reported COVID-19 deaths in twelve African countries using iterated filtering and allowing a flexible transmission rate.

Results: We observed high heterogeneity in the case-fatality rate across countries, which may be due to different reporting or testing efforts. South Africa, Tunisia, and Libya were affected most strongly, exhibiting a relatively higher $R_0(t)$ and infection attack rate.

Conclusion: To effectively control the spread of COVID-19 epidemics in Africa, there is a need to consider other mitigation strategies (such as improvements in socioeconomic well-being, healthcare systems, the water supply, and awareness campaigns).

Keywords: SARS-CoV-2, pandemic, reproduction number, attack rate, seroprevalence

1. Introduction

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a novel strain of coronavirus that has caused the current pandemic of coronavirus disease 2019 (COVID-19) and has strongly affected all six major regions of the world. Africa reported its first case of COVID-19 on February 14, 2020 in Cairo, Egypt (1-4). Since then, the disease has spread across Africa, epi-centered in South Africa, and after a year (i.e., by March 25, 2021), over 3 million people have been infected, including 76,656 thousand related deaths (1, 2, 5). The disease caused by SARS-CoV-2 emerged in China at the end of 2019 and has so far affected more than 124 million individuals and killed over 2.7 million people globally (1). COVID-19 shows a faster spreading ability than other coronaviruses of the same family (i.e., SARS-CoV and MERS-CoV) (3, 6-9). COVID-19 has also destroyed already overstretched healthcare systems and weakened the socioeconomic sector worldwide.

In the early phase of the epidemic, the twelve most-affected African countries with COVID-19 deaths were classified into three clusters/groups based on their similarity in exposure risk that originated from three Chinese provinces, namely Guangdong, Fujian, and Beijing, which represent three different levels of risks of importation (high, medium, and relatively low) (3). Each group corresponds to different Chinese airports in the associated province as the main sources of entry risk. Egypt, Algeria, and South Africa were identified as the highest importation risk groups with moderate to high magnitudes of high epidemic response followed by Nigeria, Ethiopia, Sudan, Morocco, and Kenya, which were classified as moderate importation risk groups with variable magnitudes of response to epidemics with high vulnerability. The last group includes Tunisia, Cameroon, and Zambia, and is classified as having relatively low importation risk with variable magnitude to respond to epidemics with high vulnerability (2, 3).

With vaccines being developed recently, many of them are still in clinical trials, and some are already on the market for use against COVID-19 infection (; may have this link as a reference). Nonpharmaceutical interventions (NPIs) (which include social distancing, the use of facemasks, total or partial lockdown, contact tracing, quarantine, and isolation) are currently the main strategies to mitigate/prevent the spread of COVID-19, and have helped significantly reduce the mortality rate across the globe (1, 10, 11).

Epidemiological modeling studies have long been used to understand and shed light on the transmission and spread of infectious diseases, including COVID-19 (e.g., see 3, 4, 12-14 and the references therein). Uyoga et al. (15) described/examined the seroprevalence of anti-SARS-CoV-2 immunoglobulin G antibodies among Kenyan blood donors to determine the extent to which COVID-19 spread in the community. They found that the crude seroprevalence (i.e., amount of SARS-CoV-2 pathogen in blood serum) was estimated at 5.6%, which indicates that SARS-CoV-2 exposure is more extensive than indicated by case-based surveillance. Another work (in the preprint by the submission date of this manuscript) by Sykes et al. (43) examined the seroprevalence of SARS-CoV-2 among blood donors in South Africa. The results showed that SARS-CoV-2 prevalence differs by race group and province, with seroprevalence among black donors higher than that of white donors and other main population subgroups. Their estimation of the seroprevalence (which crudely equals the infection attack rate if we

ignore seroreversion) in each of the four cities of the study area was 62.5 in Eastern Cape (95% CI: 58.9 – 66.1); 31.8 in Northern Cape (95% CI: 25.3 – 38.3); 45.5 in Free State (95% CI: 39.9 – 51.1); and 52.1 in KwaZulu Natal (95% CI: 49.1 – 55.2). These results significantly differed from the work of Uyoga et al. (15), in which the given estimates of the seroprevalence in South Africa (given by age group) ranged from 3.4 to 10.0 (95% CI: 1.6 to 19.5) and seemed to be epidemiologically more reasonable. Thus, we observed that the pandemic of COVID-19 in Africa has not been described appropriately (44).

In this paper, we study the transmission dynamics of SARS-CoV-2 in Africa. Some of the epidemiological characteristics, implementation, and implications of NPIs of SARS-CoV-2 in Africa will be discussed. In particular, $R_0(t)$ and IAR of COVID-19 for the twelve most affected African countries that experienced COVID-19-related deaths will be estimated. This will provide some useful insights and suggest effective COVID-19 control measures in Africa. NPIs play a key role in the prevention and control of the SARS-CoV-2 epidemic. However, African countries have some difficulties, especially with regard to compliance with NPIs. Thus, we report/highlight some important factors that should be emphasized/improved to effectively control the spread of the disease. Simulations have shown the estimated values of $R_0(t)$ and IAR for the top twelve countries with COVID-19-related deaths in Africa, which are vital epidemiological parameters to curtail the spread of COVID-19 in Africa and beyond.

2. Material and Methods

2.1. COVID-19 epidemic data

A set of COVID-19 observations indexed and arranged in time (16) for cases and deaths were extracted from the public domain of the World Health Organization (WHO) dashboard for disease surveillance reports of the twelve countries with the most COVID-19 deaths in Africa (Zambia, Cameroon, Nigeria, Libya, Sudan, Kenya, Ethiopia, Algeria, Tunisia, Morocco, Egypt, and South Africa), retrieved from [https://covid19.who.int/\(1\)](https://covid19.who.int/(1)). The time series distribution for the daily confirmations of COVID-19 cases and deaths for the twelve countries with the highest number of deaths in Africa by February 12, 2021 are visualized in **Figure 1**. This shows the trends of the epidemics. COVID-19 cases and deaths are represented by black and red dotted curves, respectively. Based on the data scenarios, we observed that Libya exhibited the first wave of the epidemic. Other counties have shown at least two waves of the COVID-19 epidemic patterns, with South Africa hit worst for both cases and deaths. The country's population data were obtained from the Worldometer, available via <https://www.worldometers.info/population/>. We primarily used COVID-19 deaths since the COVID-19 cases would be easily influenced by reporting policies and efforts. However, surely, COVID-19 deaths are underreported. To better understand underreporting, we obtained information on excess deaths for South Africa from online sources (<https://www.wsj.com/articles/south-africas-drop-in-covid-19-cases-adds-to-questions-about-waves-of-infections-11615734003>). We fit our model to the excess deaths with an assumed IFR at $\geq 7\%$.

2.2. The SEIHRD epidemic model

A susceptible-exposed-infectious-hospitalized-removed-dead (SEIHRD) model was proposed based on the classic SEIR-type (14, 17-19) to obtain the fitting results with biologically reasonable parameter values. The model was fitted to the data on deaths to visualize the COVID-19 scenario in the twelve most-affected countries with COVID-19 deaths in Africa in order to shed light on suitable NPIs that could appropriately and timely help to curtail outbreaks with very reduced socioeconomic consequences. In the classic SEIR-type model, the population is subdivided into four different compartments according to infection status, representing susceptible (S), exposed (E), infectious (I), and recovered (R).

Based on the general epidemiological features of SARS-CoV-2 (12, 13), we considered two additional compartments for infected individuals, which are ‘hospitalized infected’ and ‘dead’ compartments, represented by H and D , respectively. Susceptible individuals can become exposed after coming into contact with infected people. Exposed individuals can progress to the infectious compartment after the latency period. Infectious individuals can move to the hospitalized compartment, which comes from either mild or severe cases. Infectious individuals can recover/be removed following effective treatment (or naturally) or die due to the infection and enter the D compartment. The proposed model, represented by the following non-linear ordinary differential equations, is presented below.

$$\dot{S} = -\frac{\beta SI}{N},$$

$$\dot{E} = \frac{\beta SI}{N} - \sigma E,$$

$$\dot{I} = \sigma E - \gamma I,$$

$$\dot{H} = \rho \psi I - \xi H,$$

$$\dot{D} = \rho \xi H,$$

$$\dot{R} = (1 - \rho)\gamma I + (1 - \rho)\xi H.$$

Here, parameter β represents the flexible time-varying transmission rate, while parameter σ denotes the disease progression rate from the latent stage to infection status. Parameter γ measures the rate at which individuals move from I to H or R , while parameter ξ signals the SARS-CoV-2-induced death rate from the H compartment.

In this model, the parameter ρ represents both the proportion-of hospitalization among infections and the share of deaths among hospitalizations. Note that hospitalization can be interpreted as symptomatic cases. Thus, the infection fatality ratio (IFR) is given by ρ^2 . We fitted the weekly integrated D to the reported mortality data for each of the twelve countries with the highest number of COVID-19-related deaths in Africa. Note that H could also be interpreted as reported cases. Since we only fit D to reported deaths rather than H to reported cases (or hospitalization), the exact definition of H is not crucial. We

could define the proportions separately (the numbers of hospitalizations among infections, and the share of deaths among hospitalizations), but that would introduce one more parameter that would require more information or assumption with virtually the same fitting performance. Classic theory tells us that the dynamics of the model are mainly dependent on β and γ and less sensitive to other parameters.

The other assumptions include negative binominal measurement noise in reporting with an overdispersion parameter ϕ and a time-varying transmission rate (β), which is an exponential cubic spline function with 7 nodes. The effective basic reproduction number $R_0(t)$ is given by $R_0(t) \approx \beta(t)/\gamma$. For more details regarding the model fitting process, see (14, 17-19). Iterated filtering algorithms are used to fit the model with an additional death class to the reported COVID-19 deaths for the twelve countries with the most deaths in Africa to quantify epidemic scenarios in Africa using the estimate of reproduction number. Thus, the proposed model was fitted to the SARS-CoC-2 mortality data for each of the twelve African countries.

3. Results

In **Figure 2** and **Figure 3**, we used the proposed SEIHRD model to simulate the COVID-19 mortality datasets (weekly) for the twelve African countries with the most COVID-19 deaths to explore the dynamic characteristics of SARS-CoV-2 in Africa. The fitting results are used to estimate the time-varying basic reproductive number, $R_0(t)$, and the infection attack rate, IAR, for each of the twelve countries, as depicted in **Figure 2** and **Figure 3**, respectively. **Figure 2** shows the fitting results of nine of the twelve countries with the most COVID-19 deaths (Algeria, Cameroon, Egypt, Ethiopia, Kenya, Morocco, Libya, Nigeria, Sudan, Tunisia, and Zambia), which were hit milder or had a relatively lower reporting rate. **Figure 3** displays the fitting results of three of the twelve countries with the most COVID-19 deaths (Libya, South Africa, and Tunisia), which hit harder or had a relatively higher reporting rate. The weekly confirmed deaths are represented by the red circle, with the black curve representing the medium simulation, and the gray shaded region denoting the 95% confidence interval (CI). By February 2021, Cameroon, Sudan, Algeria, and Tunisia were witnessing the third wave of the COVID-19 epidemic, whereas Zambia, Nigeria, Libya, Kenya, Ethiopia, Morocco, Egypt, and South Africa were observing the second wave of the SARS-CoV-2 epidemic. The increase in transmission rate in these countries was likely due to the partial or non-compliance of the NPIs, age factor (the share of the elderly population), seasonality, or behavioral changes (see, for instance, (20)). For South Africa, we fit our model to excess deaths, as seen in **Figure 3d**. With the assumption $IFR \geq 7\%$, we yield a similar estimated IAR per using the reported COVID-19. The excess death rate is approximately 3.4-fold of the reported COVID-19 rate.

In **Table 1**, we obtained estimated values of the SARS-CoV-2 infection attack rate (IAR, the ratio of mortality per cases in a particular population) for the twelve countries with the most deaths in Africa by February 2021. South Africa was hit hardest with an IAR of 0.414, followed by Tunisia with an IAR of 0.213 and then Libya with an IAR of 0.155, while Cameroon and Algeria were hit the mildest, with IARs of 0.022 and 0.042, respectively. These results indicate the impacts of NPIs, and thus highlight the

imperative need to implement other control strategies to mitigate epidemics in Africa and beyond. Further, we assumed that ρ varies from 0.01 to 0.1; hence, the IFR varies between 0.0001 and 0.01. We presume that the reported COVID-19 deaths are relatively reliable.

In Appendix Table 1, we report the COVID-19 index case(s) scenarios for the twelve countries with the most deaths in Africa. SARS-CoV-2 was first reported in Egypt on February 14, 2020, followed by exponentially growing cases that spread in all parts of Africa, with South Africa as the epicenter until now. Consequently, the estimated seroprevalences of SARS-COV-2 (i.e., the estimated proportion of individuals in a population who test positive for COVID-19) are reported in Appendix Table 2, which indicates that South Africa has an estimated seroprevalence of approximately 50% from blood donors (48). This result highlights that South Africa has been hit harder, which may be a consequence of the high proportion of mild or asymptomatic cases, comprising up to 80% of total infections (49).

Appendix Table 3 presents the results of the model's estimated parameters by employing the log-likelihood estimation technique. South Africa, Egypt, and Tunisia have log-likelihood values of -301.112, -263.928, and -232.474, respectively. These outcomes signal that South Africa has the highest transmission potential compared to other countries. In Appendix Table 4, we present a summary of the estimated results of the time-varying transmission rate using a fixed number of nodes (n_m), 7. Different values of the time-varying transmission rate were obtained based on the different simulation runs. The state values of the model were assigned, with initial values given in Appendix Table 5.

4. Discussion: The Implementation and Implications of NPIs

It has been more than a year since COVID-19 emerged in China and spread rapidly to over 200 countries and territories. Based on the lessons learned, African countries have slightly strengthened their preparedness plans against unexpected disease outbreaks such as the COVID-19 pandemic, which includes timely responses; airport surveillance and temperature screening at ports of entry; improvement in diagnostic centers for testing/mass testing; strengthened collaboration with other countries in other regions like China, the US, and the UK (for instance, the deployment of medical personnel from the UK, donations of testing kits and PPEs by the Jack Ma foundation, etc.) (2, 3). Africa was lucky to report its first case of COVID-19 at least a month after many countries on other continents had already reported thousands of cases and deaths (1, 6, 21), making the continent advantageous over others for timely preparations and responses to the pandemic in a variety of ways based on the lessons learned.

To visualize the actual scenario of the SARS-CoV-2 situation in twelve African countries with the most deaths, we simulated the model using weekly mortality data for each of the twelve countries to guide policymaking for controlling the COVID-19 pandemic in Africa. To achieve reasonable fitting and estimates, we made some assumptions; in particular, we divided these countries into two groups. Group 1) consists of South Africa, Libya, Tunisia, with a value of ρ above 0.045 (i.e., IFR>0.2%). These countries reported more deaths per capita, which suggests a severe impact and/or efficient reporting of deaths, and their IARs were 41.4%, 15.4%, and 8.6%, respectively. Group 2) consists of nine other countries (with a value of ρ between 0.01 and 0.04, i.e., 0.01% < IFR < 0.16%), which shows mild

impact and/or underreporting of deaths. Their IAR varies between 2.2% and 20.2%, with a median of 5.7%. In **Figure 2**, we depicted the time series fitting results of weekly reported COVID-19 deaths in nine of the twelve African countries (Algeria, Cameroon, Ethiopia, Kenya, Morocco, Nigeria, Sudan, and Zambia) that were hit milder or had a low reporting rate, and **Figure 3** reveals the time series fitting results of weekly reported COVID-19 deaths in three of the twelve African countries (Libya, South Africa, and Tunisia) that were hit harder or had a relatively higher reporting rate.

Consequently, Africa's COVID-19 responses and control strategies were largely not context-specific (15, 22). The responses and mitigation strategies via NPIs employed in Africa were described as replication or simply the COVID-19 *copy-and-paste* policy that was employed in other countries, such as China, the UK, and Europe, despite the variability in epidemiological characteristics, differences in weather and climate, and different socioeconomic growth levels, which probably impact the transmission of the disease in Africa. Consistently, this *copy-and-paste* approach (also known as the 'one-size-fit-all' policy) is slightly more strenuous to properly implement and comply within Africa. In fact, some of those stringent measures were clearly needless and turned out to be useless, causing more socioeconomic hardship to many African countries. For instance, many African countries impulsively adopted the same lockdown policy together with other NPIs without the requisite knowledge of the COVID-19 features in Africa and the context-specific relevance and consequences of these measures to the community, even in the early phase of the outbreak (2).

Social distancing policies and restrictions on social gatherings (such as banning weddings, religious activities, and funeral ceremonies) have been imposed to curtail the spread of the virus, even though it is almost practically impossible for many African countries to comply with. Mandatory wearing of facemasks in public places and the use of hand sanitizers were also pervasive COVID-19 control measures in Africa, even though compliance is very difficult and problematic due to ignorance, poverty, resource constraints, and a lack of awareness (2, 22). Although some successes have been achieved with respect to these response strategies, critics have described them as *one-size-fit-all* or *copy-and-paste* approaches because of inappropriateness and unfavorability to local settings in Africa (23-25). In addition, one more important control measure is school closure, which has been massively criticized in Africa since many countries on the continent spontaneously closed down schools with the absence of exhaustive e-learning systems and inadequate infrastructure, as has been practiced in many other countries (22).

Some of the main challenges regarding the fight against the COVID-19 pandemic in Africa include the imposition of the hand-hygiene policy when the majority of Africans do not have access to an adequate and portable water supply, temperature screening at airports for travelers without considering asymptomatic carriers (asymptomatically infected people), the impossibility of work from home policies, and an insufficient quantity of PPEs, especially for frontline health workers, insufficient data sharing, and illegal crossing of borders at non-official points of entry (2, 26-28,50).

Food prices have skyrocketed significantly in many countries on the continent during lockdowns due to panic buying and interruptions in the food supply chain within the community and between countries (29). Although lockdowns have helped to control the spread of the disease, they (2, 22, 23) plunged

millions of people into extreme poverty, which likely has greater consequences and can kill more people than COVID-19 due to its negative impacts that have exhausted countless individuals (22). Aside from the extreme poverty caused (likely) due to the effects of lockdowns, there were issues of human rights abuses by government officials or security agencies that add up to the hardships already emanating from the lockdown policy in Africa (30).

Another unexpected repercussion of NPIs in Africa was the effect of already fragile healthcare systems. Neglecting public health needs in the wake of COVID-19 has been reported with an unprecedented reduction in health service usage, causing more threats concerning other infectious illnesses such as malaria, HIV/AIDS, and meningitis (31-33). These implications may even cause more serious consequences during the post-COVID-19 pandemic because of their socioeconomic destruction. We also observed that most of the top twelve African countries with most COVID-19 deaths reported their first COVID-19 case(s) between February and March 2020 (see Appendix Table 1), which indicates that most of the stringency index policies are similar in most countries in Africa.

5. Conclusion

Overall, Africa has done remarkably well in terms of awareness and enlightenment campaigns by the media and civil society in disseminating health education and communication on COVID-19 prevention and control, which helps in curtailing the spread of SARS-CoV-2 in the African region (2). Even though a more favorable/suitable policy needs to be considered, it can be implemented and easily complied with by the general public to effectively control the spread of COVID-19, with very reduced economic hardships and negative consequences, especially during a post-COVID-19 pandemic. With the assumed range of IFR and flexible transmission rate, we model a unified simple model of the reported deaths in twelve African countries. The choice of group for countries was justified by the tests per capita performed across countries and the raw case-fatality rate across counties (Appendix Table 6). For instance, South Africa performed more tests per capita than other countries, which implies a relatively higher reporting effort. The raw case fatality rate is high in South Africa. Combining these two aspects, we decide to allocate South Africa to the high ρ group. Our fitting result reveals that South Africa, Libya, Tunisia, Ethiopia, and Morocco were hit harder with the SAR-CoV-2 epidemic in Africa. Thus, we suggest an imperative need to improve the socioeconomic situation, quality water supply, and healthcare system (which includes the provision of adequate health workers, PPEs, and test kits) in Africa to effectively and timely control SARS-CoV-2 outbreaks.

In this work, we proposed a simple unified model and fit the model to reported deaths in twelve African countries and excess deaths in South Africa. We gain a qualitative idea of the severity in African countries. In the next step, we plan to associate the reconstructed $R_0(t)$ with government control measures and possible voluntary social distancing in each country.

In sum, we conducted large-scale data analysis and modeling work of twelve African countries, and shed light on the possible IFR and infection attack rate. We found large variation across countries, which could be due to different economic levels, control measures, and testing and report efforts. Our estimated infection attack rates, which are based on the assumed range of IFR, are largely in line with population-level serological studies. Our work is of importance since it is the first large-scale

population-level modeling work for these African countries. Along with population-level serological studies, our work provides insight into the possible severity in these countries.

Declarations

Ethics approval and consent to participate

Ethics approval was not required.

Consent to publish

All authors read and revised the manuscript and gave consent for publication.

Availability of data and materials

All data used were obtained from the public domain, available from <https://covid19.who.int/>.

Competing interests

DH was supported by an Alibaba (China) Co. Ltd. Collaborative Research grant. SL was supported by a grant from the Guangdong Recruitment Program of Foreign Experts. The other authors declare no competing interests.

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Authors' contributions

Conceptualization: SSM & DH; Formal analysis: SSM, SZ, XW, NH, WW and DH; Writing – original draft: SSM, SZ, XW, NH, WW and DH; Writing – review & editing: SL and DH.

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Figure 1: Daily confirmed cases (in black triangles) and deaths (in red triangles) of COVID-19 in twelve African countries with the most cases of deaths from COVID-19 (population standardized, cases and deaths per 1 million people).

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Figure 3: Time series fitting results of weekly confirmed COVID-19 deaths (in red circles) in three of the twelve African countries with most COVID-19 deaths, which were hit harder (or with a relatively higher reporting effort): (a) Libya, (b) South Africa, (c) Tunisia, (d) South Africa with excess deaths. Deaths are population standardized (i.e., deaths per 1 million people). The medium of the simulation is represented by the black curve, and the time varying basic reproductive number ($R_0(t)$) is denoted by the blue dashed curve. The 95% confidence interval of the simulation is shown by the shaded (gray) region. The estimated IAR is portrayed in the title of each panel.

Table 1: Results of the infection attack rates (IARs) for the twelve African countries with the most COVID-19 deaths by the end of February 2021.

Country	Population size	Reported deaths	Est. Infection attack rate
Algeria	43,851,044	2,973	0.042
Cameroon	26,545,863	523	0.022
Egypt	102,334,404	10,541	0.064
Ethiopia	114,963,588	2,321	0.202
Kenya	53,771,296	1,847	0.052
Libya	6,871,292	2,156	0.155
Morocco	36,910,560	8,598	0.15
Nigeria	206,139,589	1,891	0.046
South Africa	59,308,690	49,667	0.414
Sudan	43,849,260	1,880	0.052
Tunisia	11,818,619	7,911	0.213
Zambia	18,383,955	1,059	0.084

Appendices

Appendix Table 1: Index case(s) of COVID-19 for the top twelve African countries with the most COVID-19 deaths by February 2021.

Country	Case	Index case confirmation	Case history	References
Algeria	110049	25 Feb, 2020	Italian from Italy to Algeria	(34)
Cameroon	31394	6 Mar, 2020	French national from French to Yaoundé	(35)
Egypt	171993	14 Feb, 2020	Chinese from China to Egypt	(3)
Ethiopia	144862	13 Mar, 2020	Japanese from Japan Burkina Faso via Ethiopia	(34)
Kenya	102353	12 Mar, 2020	Kenyan from the US to Kenya via the UK	(36)
Libya	126361	24 Mar, 2020	Returned traveler from Saudi Arabia	(37)
Morocco	477160	2 Mar, 2020	Returned Moroccan from Italy	(38)
Nigeria	143561	27 Feb, 2020	Italian from Milan to Lagos	(39)
South Africa	1484900	5 Mar, 2020	Returned traveler from Italy	(33, 40)
Sudan	29952	13 Mar, 2020	Traveler from the United Arab Emirates	(34)

Tunisia	220478	2 Mar, 2020	Returned Tunisian from Italy	(41)
Zambia	66598	18 Mar, 2020	Returned travelers from France via the United Arab Emirates	(42)

Appendix Table 2: Summary table of the estimated seroprevalence of SARS-CoV-2 in twelve African countries with the most deaths.

Country	Estimated seroprevalence percentage (95% CI)	Refs
Algeria	Na	
Cameroon	Na	
Egypt	4.4 (3.6 - 5.3)	(45)
Ethiopia	3	(44)
Kenya	4.3 (2.9 – 5.8)	(15)
Libya	2.74	(46)
Morocco	Na	
Nigeria	45.1 (in frontline healthcare workers)	(44, 47)
South Africa	47.975 (43.3 – 52.675)	(43)
Sudan	Na	
Zambia	Na	

Appendix Table 3: Parameter setting and estimates log likelihood.

<i>Country</i>	<i>Loglik</i>	<i>loglik.sd</i>	σ	ρ	γ	ξ	<i>Population</i>
Algeria	-224.253	0.029	182.5	0.04	121.667	30.42	43,851,044
Cameroon	-144.127	0.039	182.5	0.03	121.667	30.42	26,545,863
Egypt	-263.928	0.057	182.5	0.04	121.667	30.42	102,334,404
Ethiopia	-163.456	0.121	182.5	0.01	121.667	30.42	114,963,588
Kenya	-180.626	0.032	182.5	0.026	121.667	30.42	53,771,296
Libya	-152.392	0.129	182.5	0.045	121.667	30.42	6,871,292
Morocco	-228.438	0.086	182.5	0.039	121.667	30.42	36,910,560
Nigeria	-169.985	0.07	182.5	0.014	121.667	30.42	206,139,589
South Africa	-301.112	0.052	182.5	0.045	121.667	30.42	59,308,690
Sudan	-204.765	0.019	182.5	0.027	121.667	30.42	43,849,260
Tunisia	-232.474	7.476	182.5	0.088	121.667	30.42	11,818,619
Zambia	-146.848	0.091	182.5	0.026	121.667	30.42	18,383,955

Appendix Table 4: Estimates of node values of the time varying transmission rate.

<i>Country</i>	n_m	<i>log.beta</i>	<i>log.beta1</i>	<i>log.beta2</i>	<i>log.beta3</i>	<i>log.beta4</i>	<i>log.beta5</i>	<i>log.beta6</i>
Algeria	7	5.0085	4.618	4.7797	4.6275	4.8575	4.4571	5.0695
Cameroon	7	5.233	4.8013	4.4089	4.7312	4.6758	4.8319	5.2296
Egypt	7	4.9114	4.933	4.5948	4.6307	4.8223	4.8586	4.5068
Ethiopia	7	5.4317	4.8883	4.9975	4.6998	4.9516	4.9207	5.3602
Kenya	7	4.9747	4.9008	4.7466	4.724	4.7922	4.433	5.4337
Libya	7	4.6074	4.8976	4.9502	4.7852	4.7528	4.8624	4.7877
Morocco	7	4.8897	4.448	5.0903	4.7568	4.8531	4.627	4.8797
Nigeria	7	5.4681	4.8345	4.6533	4.4809	4.8602	4.9109	4.6148
South Africa	7	5.191	5.0202	4.8431	4.7073	4.9659	5.1832	4.4887
Sudan	7	5.2186	5.0223	4.3629	4.619	5.2147	4.331	5.1936
Tunisia	7	4.5318	4.4076	4.6533	5.3055	4.6676	4.8369	4.4059
Zambia	7	4.3986	5.0439	4.8931	4.3508	4.7816	5.1662	4.1408

Appendix Table 5: Estimated initial values of the state variable of the model.

Country	ϕ	$S(0)$	$E(0)$	$I(0)$	$H(0)$	$D(0)$	$R(0)$
Algeria	0.1036	41658492	5047	5047	505	50	2181902
Cameroon	0.4824	25218570	392	392	39	4	1326467
Egypt	0.0597	97217684	4318	4318	432	43	5107609
Ethiopia	0.0015	109215409	125	125	12	1	5747916
Kenya	0.0601	51082731	494	494	49	5	2687521
Libya	0.0063	6527727	117	117	12	1	343317
Morocco	0.0236	35065032	3765	3765	376	38	1837584
Nigeria	0.0048	195832610	506	506	51	5	10305912
South Africa	0.0389	56343255	271	271	27	3	2964864
Sudan	0.8388	41656797	186	186	19	2	2192070
Tunisia	0.0001	11227688	569	569	57	6	589730
Zambia	0.0055	17464757	423	423	42	4	918305

Appendix Table 6: Reported cases and tests. Data from <https://www.worldometers.info/> by March 7, 2021.

Country	Reported cases	Test performed	Test per 1 m population	Positive rate (per test)	Raw case-fatality rate
Algeria	114234	NA	NA	NA	0.0264
Cameroon	35714	905000	33529	0.0395	0.0154
Egypt	186503	1e+06	9649	0.1865	0.059
Ethiopia	166138	2178403	18637	0.0763	0.0146
Kenya	108827	1333690	24439	0.0816	0.0172
Libya	138640	752060	108448	0.1843	0.0164
Morocco	486223	5729423	153984	0.0849	0.0179
Nigeria	158506	1580442	7541	0.1003	0.0124
South Africa	1521068	9255492	154731	0.1643	0.0333
Sudan	28605	NA	NA	NA	0.0662
Tunisia	237704	1004877	84424	0.2366	0.0345
Zambia	82421	1131606	60414	0.0728	0.0136

Figures

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