CLIMATIC DETERMINANTS OF COVID-19 CASES AND DEATHS IN UGANDA: 2020-2022

*Justine Okello[1,2], Luke Nyakarahuka[1,2], Muleme James[1,3], Collins Atuheire[1], George Seruwagi[1,6], Opiyo Felix Lakor[1], Kakuru Glet Bitariho[1,4], Muwanguzi David[4], Andrew Malata Phiri[5], Musso Munyeme[4], Clovice Kankya[1], Lian Thomas[7]

Affiliations

[1]Department of Biosecurity, Ecosystems and Veterinary Public Health, School of Biotechnical, Biosecurity and Laboratory Sciences, College of Veterinary Medicine, Animal resources and Biosecurity, Makerere University P.O. Box 7062, Kampala, Uganda

[2]Unit of Viral Haemorrhagic fevers, Uganda Virus Research Institute, Entebbe Uganda

[3]Department of Disease control, School of public Health, Makerere University P.O. Box 7062, Kampala, Uganda, Uganda

[4]Department of Epidemiology, surveillance and Public health, Ministry of Health Uganda, P.O.Box 7272 Kampala, Uganda

[5]School of Veterinary Medicine, University of Zambia, P.O.Box 32379, 10101 Lusaka Zambia

[6]Department of Mathematics, college of Natural Sciences, Makerere University P.O. Box 7062, Kampala, Uganda, Uganda,

International Livestock research Institute, Nairobi, Kenya

*Corresponding author: justinokello01@gmail.com, +256783210265

ABSTRACT

Background: Infectious diseases have proven to be among the greatest challenges to life in the Anthropocene era. Their repeated and cyclical occurrences coupled with varying variants, and rapidly changing climatic conditions within this century threaten to take the world back to the "*pre-development era*" in the absence of corrective measures. We designed a research study to determine the influence of weather parameters on the spread of COVID-19 in Uganda from March 2020 to January 2022.

Methods: Records of COVID-19 mortalities and morbidities as well as weather elements from March 2020 to January 2022 were retrieved from the national data bases of the Ministry of Health and Meteorological Authority, respectively. Data analysis was conducted in STATA/SE 17.0. A generalized simple linear regression model was conducted to explore the climatic determinants of COVID-19 cases and deaths using the different predictor variables bivariate and multivariate regression analyses were conducted. A set of SEIR differential equations were analyzed to study the dynamics of COVID-19 with vaccination and temperature variations. The reproduction number and disease-free equilibrium were also analyzed. Simulations for to determine the behavior of COVID-19 with vaccination and varying temperature were performed using MATLAB software.

Results: Mean COVID-19 cases started gradually from the month of March 2020 at means of fewer than 10 cases till July 2020. From August to December 2020, the mean COVID-19 cases increased rapidly with mean cases of about 400 cases by the end of December 2020. a unit increase in the daily maximum temperature, the number of COVID-19 cases increased at 22.57 times [(95%CI =13.08-32.05), p-value <0.001]. Also, a unit increase in the daily temperature range, COVID-19 cases increased at 27.81 times [(95%CI = 17.60-38.01), p-value <0.001].

Conclusion: The present study reveals that different environmental weather parameters affected the deaths and cases of COVID-19. Increase in the daily maximum temperature resulted in the decrease of COVID-19 cases and deaths. Increase in the daily relative humidity resulted in to decrease of COVID-19 cases and deaths. Specifically, increase in the daily Rainfall amounts resulted in to decrease and increase in the number of COVID-19 cases and deaths respectively. The same trend was exhibited by the daily windspeed.

INTRODUCTION

Background

Infectious diseases have proven to be among the greatest challenges to life in the Anthropocene era (Kronfeld-Schor *et al.,* 2021; Al-Awadhi *et al.,* 2020). Their repeated and cyclical occurrences coupled with varying variants, and rapidly changing climatic conditions within this century threaten to take the world back to the "*pre-development era*" in the absence of corrective measures. This is clearly evident from the COVID-19 pandemic that caused havoc and crippled trade, education, social life patterns and other vital economic sectors worldwide (Ukhurebor *et al.,* 2021).

Starting as an unspecified etiological outbreak in a live wet animal market in Wuhan china, Severe Acute Respiratory Syndrome Corona viruses-2 (SARs-COV-2) culminated into the coronavirus disease (COVID-19) pandemic (Salzberger *et al.,* 2020). COVID-19 became one of the major leading causes of hospitalizations and deaths globally with about 200 million confirmed cases and over 4 million people already dead (WHO, 2020 and Yang *et al.,* 2020). It is also remarkable that the burden of this zoonotic COVID-19 was felt unevenly by different regions and varying conditions world-over (Walle-Hansen *et al.,* 2021). In both first and second waves, Sub Saharan African region presented with a lower number of COVID-19 cases and mortalities compared to America, Europe and Asia. However, it is evident that there is a heterogeneous (non-uniform) distribution of the disease within the African region (Salyer *et al.,* 2021).

On 21st March 2020, Uganda registered her first reported case of COVID-19 involving a Ugandan adult male who arrived from Dubai marking the beginning of the country's first wave of the disease (Migisha *et al.,* 2020). By May 6th, 2020, the county had a total of 100 confirmed cases. This number increased by over 150% in a period of 14 days (Migisha *et al.,* 2020). By July 23rd 2020, the country registered a first death (MOH, 2020) with 1,079 confirmed cases in a period of two months. As of 14th February 2022, the country had already registered about 162,693 confirmed cases and 3,572 deaths with over 60% of the statistics derived from waves after the first wave of the disease (*COVID Live Worldometer*, 2022). Much as there was an increasing number of cases registered on contact, community transmission of the disease is believed to have increased in parallel.

Even though Uganda generally has a warm tropical climate modified and characterized by warm/hot and a cold/wet seasons, the country experiences different and varying climatic types/conditions including equatorial, Savanah, montane and semi-desert climate (Kisembe *et al.,* 2019). These climatic conditions have been shown to have varying weather conditions of high temperatures, humidity among others (Egeru *et al.,* 2019). Further, the climatic conditions especially those experienced in the western part of Uganda have been shown to support the proliferation and propagation of disease pathogens like those of the Ebola Virus among others (Nyakarahuka *et al.,* 2017).

In addition, sparsely populated areas of the country have been reported to have lower transmission rates, especially when compared to more densely populated localities with higher transport networks and higher mobility of contacts and thus driving exposures. Currently, what is known is that cold and wet conditions might promote longer survival of the virus in the environment (X. Liu *et al.,* 2021). It is thus imperative to note that the different factors confound the climatic drivers of COVID-19 cases. The diversity of the demographic variables of the different populations have been shown to have impacts on the cases across the different populations (Goujon *et al.,* 2021). It is further stated that lower relative humidity was associated with increased occurrence of COVID-19 cases; a reduction in relative humidity of 1% was predicted to be associated with an increase COVID-19 cases by 6.11%. Unique in Pakistan, the correlation between the COVID-19 cases and humidity was negative. Implying that for the increase in the unit of humidity was protective and beneficial for stopping the transmission of the disease COVID-19. This could be understood that aqueous/humid environment denatures the viral structure and hence limits its transmission.

Importantly in all the above different climatic regions of the Uganda, COVID-19 cases have been registered, and reported but to a lesser extent, the epidemiological burden linked to weather variability of the disease documented. Even though little is known about the disease, especially its transmissibility, the distribution and incidence of COVID-19 disease infections within the diverse climatic regions of Uganda has been underexplored and unexplored. We designed a research study to determine the influence of weather parameters on the spread of COVID-19 in Uganda from March 2020 to January 2022.

MATERIALS AND METHODS

Study design

This was a retrospective longitudinal research design to determine the relationship and influence of nine (9) predictor climatic variables and two outcome variables (COVID-19 cases and Deaths) in Uganda from March 2020 and January 2022.

Study Area

This study was undertaken in Uganda which is an agriculture-based developing country in East Africa. It is a land-locked country with an elevation of 1100m, longitude 32^{0}17`24.99s"E and latitude $1^{0}$22`24"N at easting 421,045.88 and 151806.57. The population of Uganda is estimated at 48,033,233 as of Friday, February 4, 2022, based on Worldometer elaboration of the latest United Nations data (*Uganda Population - Worldometer*, 2022). The population density in Uganda is 229 per Km^2 (*Uganda Population (2022) - Worldometer*, 2022).

Data collection

Records of COVID-19 mortalities and morbidities as well as weather elements from March 2020 to January 2022 were retrieved from the national data bases of the Ministry of Health and Meteorological Authority, respectively. The data obtained from the Ministry of Health data base had been collected from various districts of Uganda and uploaded to the database through National Health Information Management System (HIMS). A case data included the laboratory finding, that was linked to the demographic characteristics of the victims. However, the HIMS systems captured the absolute daily numbers of cases and deaths. Weather records were obtained from selected meteorological stations in the climatic regions of Uganda from the archives at the Uganda Meteorological Authority. The outcome variables extracted included numbers of deaths and cases due to COVID-19. Also, the independent variables included the daily temperature (minimum, maximum and range), Relative Humidity, precipitation (rainfall), surface pressure and wind speed (average, minimum and maximum) recordings.

Data Analysis

The data obtained were re-organized in MS Excel (Microsoft Corporation, USA 2021 series) and then later exported to STATA/SE 16.0 where descriptive statistics were conducted to determine the summary of measures for the variables under investigation and the different parametric tests as shown hereunder to answer research aim. A generalized simple linear regression model was conducted to explore the climatic determinants of COVID-19 cases and deaths using the different predictor variables (the meteorological weather parameters). Both bivariate and multivariate regression analyses were conducted. The bivariate regression analysis explored the monotonic relationship of each of the climatic determinants on the outcome variables of interest. The multivariate regression analysis explored the polytonic relationship of the model predictor variables to the outcomes. To identify the variables to include in the multivariate analysis, the highest adjusted R^2 which incorporates the modules degree of free and the lowest RMS were considered for inclusion. Most importantly, to avoid the regression coefficients becoming unstable and standard errors getting inflated, and as well to determine a perfect relationship between predictor variables; multicollinearity was assessed using an inflation statistic called variance inflation factor with the command VIF in STATA. A variable whose VIF was greater than 10 or tolerance (1/VIF) was included in the model. Also, the plausibility of the predictor variable was considered for inclusion in the model. To determine how accurately the model predicts the response, the most important criterion for the fit in the main purpose of prediction the RMSE (Root of variance of the residuals), and the lowest was taken into consideration for the best model of prediction.

A set of SEIR differential equations were analyzed to study the dynamics of COVID-19 with vaccination and temperature variations. The reproduction number and disease free equilibrium were also analyzed. Simulations for to determine the behavior of COVID-19 with vaccination and varying temperature were performed using MATLAB software.

A Generalized Susceptible-Exposed-Infected-recovered (SEIR) compartmentalized model with vaccination

We extended the general SEIR model to include vaccination compartment. But first, we began by stating some assumptions that guided our model formulation.

Assumptions

(i) The size of the total population remains constant. That is, $N = S(t) + E(t) + I(t) + R(t)$.

(ii) Susceptible individuals are recruited into the S compartment at a constant rate, Λ.

(iii) The transmission rate from an exposed person to a susceptible is β_1 and the transmission rate from an infectious person to a susceptible is β_2. Here, we assume that $\beta_1 < \beta_2$. This means the disease is more likely to spread from an infectious individual than from an exposed individual.

(iv) Individuals in the exposed (E) compartment have a short incubation period. Some become infectious and move to the infected (I) compartment at the rate γ. Whereas, some recover and move to the recovered (R) compartment at the rate σ.

(v) When becoming infectious, individuals can recover from the disease and move to the recovered (R) compartment at the rate κ. In contrast, some perish by the disease at the rate δ.

(vi) Recoveries are assumed to be permanent.

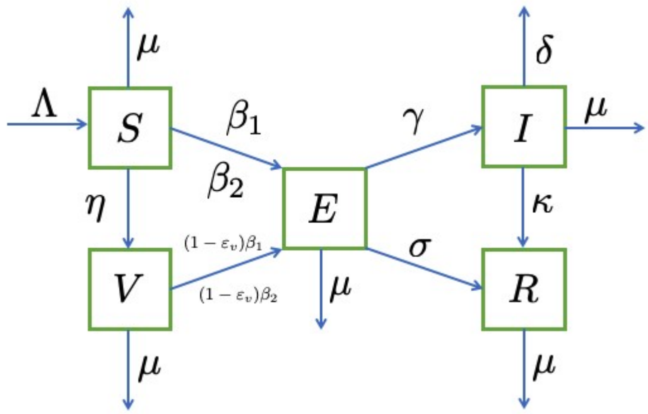
(vii) Natural mortality occurs in all compartments at the rate μ.

(viii) All parameters in the model are positive.

Given the above assumptions, we formulate an *SEIR* model with a vaccination compartment. In this study, we have also noted that the virus can still be transmissible to vaccinated individuals with a reduced rate of $(1-\varepsilon_v)\beta_1$ from an exposed person and $(1-\varepsilon_v)\beta_2$ from an infectious person. Thus, the system of the ordinary differential equations is presented as follows:

$$
\begin{aligned}
\frac{dS}{dt} &= \Lambda - \eta S(t) - \beta_1 S(t)E(t) - \beta_2 S(t)I(t) - \mu S(t),\\
\frac{dV}{dt} &= \eta S(t) - (1-\varepsilon_v)\beta_1 V(t)E(t) - (1-\varepsilon_v)\beta_2 V(t)I(t) - \mu V(t),\\
\frac{dE}{dt} &= \beta_1 S(t)E(t) + \beta_2 S(t)I(t) + (1-\varepsilon_v)\beta_1 V(t)E(t) + (1-\varepsilon_v)\beta_2 V(t)I(t) - \gamma E(t) - \sigma E(t) - \mu E(t)\\
\frac{dI}{dt} &= \gamma E(t) - \kappa I(t) - \delta I(t) - \mu I(t),\\
\frac{dR}{dt} &= \sigma E(t) + \kappa I(t) - \mu R(t).
\end{aligned}
$$

The compartment diagram and parameter description of the *SEIR* with vaccine are given below;



Parameters	Description
Λ	recruitment rate
β_1	rate of contraction of susceptible from exposed
β_2	rate of contraction of susceptible from infectious
γ	rate at which an exposed individual becomes infectious
σ	rate at which an exposed individual recovers
κ	rate at which an infectious individual recovers
δ	disease-induced death rate
μ	natural death rate
ε_v	vaccine efficacy against acquisition of infection (degree of protection)
η	vaccination rate

Basic Reproduction Number

We proceeded to calculate the basic reproduction number of System of differential equations above as follows:

$$\frac{dE}{dt} = \beta_1 S(t)E(t) + \beta_2 S(t)I(t) + (1-\varepsilon_v)\beta_1 V(t)E(t) + (1-\varepsilon_v)\beta_2 V(t)I(t) - \gamma E(t) - \sigma E(t) - \mu E(t)$$
$$\frac{dI}{dt} = \gamma E(t) - \kappa I(t) - \delta I(t) - \mu I(t).$$
,

Then,

$F_1 = \beta_1 S(t)E(t) + \beta_2 S(t)I(t) + (1-\varepsilon_v)\beta_1 V(t)E(t) + (1-\varepsilon_v)\beta_2 V(t)I(t),$

$F_2 = 0,$

$V_1 = \gamma E(t) + \sigma E(t) + \mu E(t),$

$V_2 = -\gamma E(t) + \kappa I(t) + \delta I(t) + \mu I(t).$

Then the matrices F and V evaluated at the DFE are

$$F = \begin{bmatrix} \frac{\partial \mathcal{F}_1}{\partial E} & \frac{\partial \mathcal{F}_1}{\partial I} \\ \frac{\partial \mathcal{F}_2}{\partial E} & \frac{\partial \mathcal{F}_2}{\partial I} \end{bmatrix} = \begin{bmatrix} \beta_1 S_v^0 + (1-\varepsilon_v)\beta_1 V^0 & \beta_2 S_v^0 + (1-\varepsilon_v)\beta_2 V^0 \\ 0 & 0 \end{bmatrix}$$

$$V = \begin{bmatrix} \frac{\partial \mathcal{V}_1}{\partial E} & \frac{\partial \mathcal{V}_1}{\partial I} \\ \frac{\partial \mathcal{V}_2}{\partial E} & \frac{\partial \mathcal{V}_2}{\partial I} \end{bmatrix} = \begin{bmatrix} \gamma+\sigma+\mu & 0 \\ -\gamma & \kappa+\delta+\mu \end{bmatrix} = \begin{bmatrix} k_1 & 0 \\ -\gamma & k_2 \end{bmatrix}.$$

,

Then the basic reproduction number is calculated as

$$\begin{aligned} FV^{-1} &= \frac{1}{k_1 k_2} \begin{bmatrix} \beta_1 S_v^0 + (1-\varepsilon_v)\beta_1 V^0 & \beta_2 S_v^0 + (1-\varepsilon_v)\beta_2 V^0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} k_2 & 0 \\ \gamma & k_1 \end{bmatrix}, \\ &= \frac{1}{k_1 k_2} \begin{bmatrix} (\beta_1 S_v^0 + (1-\varepsilon_v)\beta_1 V^0)k_2 + (\beta_2 S_v^0 + (1-\varepsilon_v)\beta_2 V^0)\gamma & (\beta_2 S_v^0 + (1-\varepsilon_v)\beta_2 V^0)k_1 \\ 0 & 0 \end{bmatrix} \\ &= \begin{bmatrix} \frac{(\beta_1 S_v^0 + (1-\varepsilon_v)\beta_1 V^0)k_2 + (\beta_2 S_v^0 + (1-\varepsilon_v)\beta_2 V^0)\gamma}{k_1 k_2} & \frac{(\beta_2 S_v^0 + (1-\varepsilon_v)\beta_2 V^0)k_1}{k_1 k_2} \\ 0 & 0 \end{bmatrix}. \end{aligned}$$

,

The basic reproduction number is the dominant eigenvalue of the matrix FV^{-1}. Since the matrix FV^{-1} is an upper triangular matrix, the eigenvalues are the entries on the main diagonal. Thus, the basic reproduction number is

$$\mathcal{R}_0^v = \frac{(\beta_1 S_v^0 + (1-\varepsilon_v)\beta_1 V^0)k_2 + (\beta_2 S_v^0 + (1-\varepsilon_v)\beta_2 V^0)\gamma}{k_1 k_2},$$

or,

$$\mathcal{R}_0^v = \mathcal{R}_0^{S_v^0} + \mathcal{R}_0^{V^0},$$

where

$$\begin{aligned} \mathcal{R}_0^{S_v^0} &= \frac{1}{\gamma+\sigma+\mu} \cdot \beta_1 S_v^0 + \frac{\gamma}{\gamma+\sigma+\mu} \cdot \frac{1}{\kappa+\delta+\mu} \cdot \beta_2 S_v^0, \\ \mathcal{R}_0^{V^0} &= \frac{1}{\gamma+\sigma+\mu} \cdot (1-\varepsilon_v)\beta_1 V^0 + \frac{\gamma}{\gamma+\sigma+\mu} \cdot \frac{1}{\kappa+\mu+\delta} \cdot (1-\varepsilon_v)\beta_2 V^0 \end{aligned}$$

.

Here, $\beta_1 S_v^0$ is the rate of contraction of the virus of S_v^0 susceptible individuals from exposed individuals, $(1-\varepsilon_v)\beta_1 V^0$ is the rate of contraction of the virus of V^0 vaccinated individuals from exposed individuals, and $\frac{1}{\gamma+\sigma+\mu}$ is the meantime in compartment E. Also, $\beta_2 S_v^0$ is the rate of contraction of the virus of S_v^0 susceptible individuals from infectious individuals, $(1-\varepsilon_v)\beta_2 V^0$ is the rate of contraction of the virus of V^0 vaccinated individuals from infectious individuals, $\frac{\gamma}{\gamma+\sigma+\mu}$ is the progression from compartment E to compartment I, and $\frac{1}{\kappa+\delta+\mu}$ is the meantime in compartment I. Thus, the reproduction number $\mathcal{R}_0^v$ is the expected number of secondary infections produced in compartment E by an exposed or infectious individual.

Disease-free Equilibrium of the Vaccine Model

The basic reproduction number of the vaccine model is estimated based on the disease-free equilibrium (DFE), denoted as $\mathcal{E}_v^0 = (S_v^0, V^0, E_v^0, I_v^0, R_v^0)$. To determine the solutions we set each equation of System (3.6) equal to zero. In other words,

$$\Lambda - \eta S(t) - \beta_1 S(t)E(t) - \beta_2 S(t)I(t) - \mu S(t) = 0,$$

$$\eta S(t) - (1-\varepsilon_v)\beta_1 V(t)E(t) - (1-\varepsilon_v)\beta_2 V(t)I(t) - \mu V(t) = 0,$$

$$\beta_1 S(t)E(t) + \beta_2 S(t)I(t) + (1-\varepsilon_v)\beta_1 V(t)E(t) + (1-\varepsilon_v)\beta_2 V(t)I(t) - \gamma E(t) - \sigma E(t) - \mu E(t) = 0,$$

$$\gamma E(t) - \kappa I(t) - \delta I(t) - \mu I(t) = 0, \ \sigma E(t) + \kappa I(t) - \mu R(t) = 0.$$

Since there is no disease present in the population, we set $E_v{}^0 = 0$, $I_v{}^0 = 0$, and $R_v{}^0 = 0$. This yields

$$S_v^0 = \frac{\Lambda}{\eta+\mu},$$
$$V^0 = \frac{\Lambda}{\eta+\mu}\cdot\frac{\eta}{\mu}.$$

Thus, the DFE point is $\mathcal{E}_v^0 = \left(\frac{\Lambda}{\eta+\mu}, \frac{\Lambda\cdot\eta}{\mu(\eta+\mu)}, 0, 0, 0\right)$.

RESULTS

Descriptive statistics for the Predictor and Outcome Variables

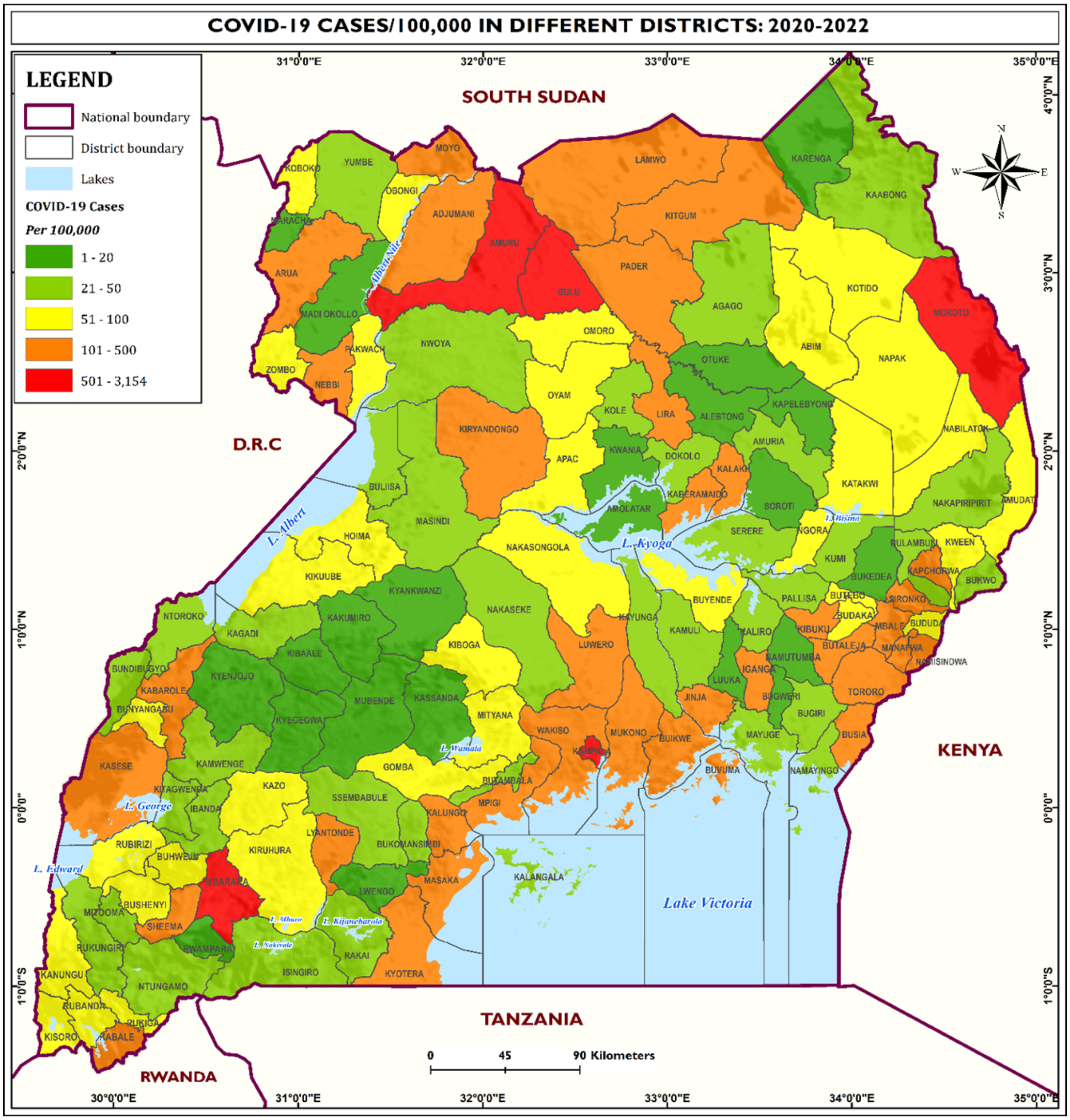
From Table 1 below, a total of 141, 584 and 3,540 COVID-19 cases and deaths, respectively, had been recorded by January 31st 2022. The mean (SD) for COVID-19 cases was 208 (±80.0) whereas the COVID-19 deaths was 5.0(1.0). The environmental parameters had approximately the same mean and median.

Table 1**:** Showing monthly mean (S.E) and the median (S.D) measures of central tendencies and dispersions for the different study variables

Variable	**Sum(N)**	**Mean(S.E)**	**Median(S.D)**
COVID-19 cases	141584	208±12.6	80.0±330.2
COVID-19 deaths	3540	5(1.2)	1.0(31.4)
TEMP MAX (^{0}C)		28.8(0.1)	28.8(2.5)
TEMP MIN (^{0}C)		19.8(0.1)	19.9(0.1)
TEMP RANGE (^{0}C)		8.9(0.1)	8.9(0.9)
Relative Humidity (%)		69.1(0.4)	69.1(0.4)
Rainfall (mm/day)		2.6(0.2)	1.0(4.7)
Surface pressure (kPa)		89.5(0.01)	89.5(0.13)
Wind speed Average(ms^{-1})		2.8(0.3)	2.7(0.9)
Wind speed MAX(ms^{-1})		4.5(0.5)	4.3(1.4)
Wind speed MIN(ms^{-1})		1.3(0.03)	1.2(0.8)

The distribution of COVID-19 cases and deaths in different parts of Uganda

Figure 2: The map of Uganda showing the spatial distribution of COVID-19 as of 31.Jan. 2022



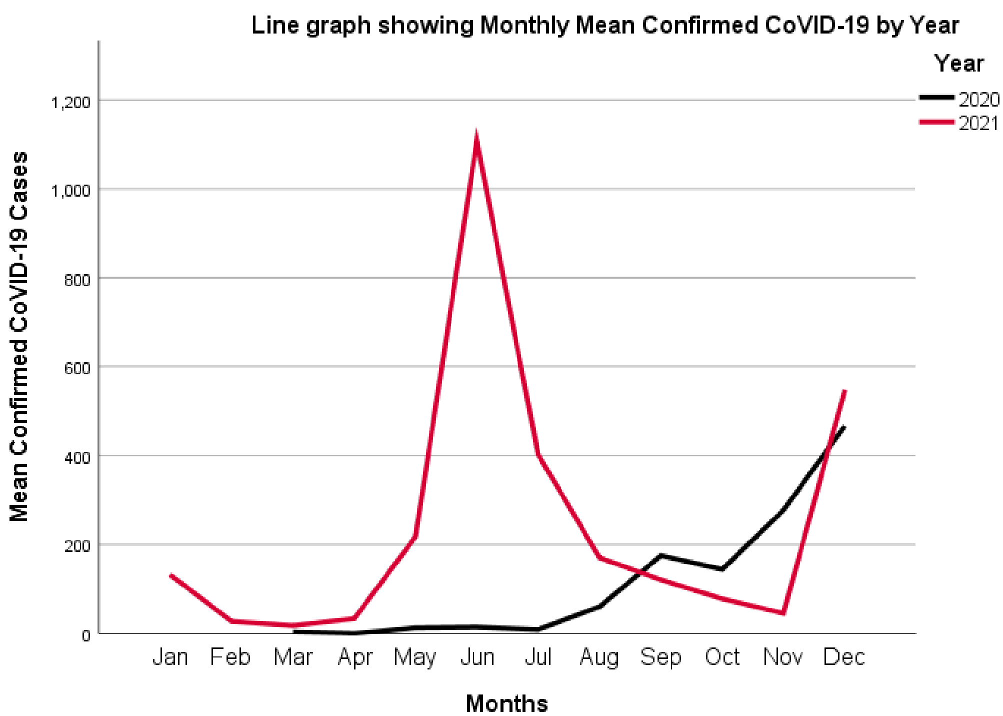
From the above fig 2, districts of Amuru, Gulu, Moroto, Mbarara and Kampala presented with highest COVID-19 cases per 100,000 ranging from 501 to 3,154. Different regions of Uganda presented with different COVID-19 cases per 100,000. And remarkably these regions present with different climatic conditions shown in fig2 below.

Trends of COVID-19 Cases

From the observed Figure 2 above, the mean COVID-19 cases started gradually from the month of March 2020 at means of fewer than 10 cases till July 2020. From August to December 2020, the mean COVID-19 cases increased rapidly with mean cases of about 400 cases by the end of December 2020.

In January 2021, the mean number of COVID-19 cases gradually decreased till about April with an average monthly mean of fewer than 200 cases across the different months in between. From April to June, the monthly mean number of COVID-19 cases exponentially increased to the maximum of over 1000 cases by June and exponentially decreased to less than 200 by the month of August 2021. The decrease continued gradually to the mean cases of 50 cases by November. Between November and December 2021, an exponential increase in the cases has been observed.

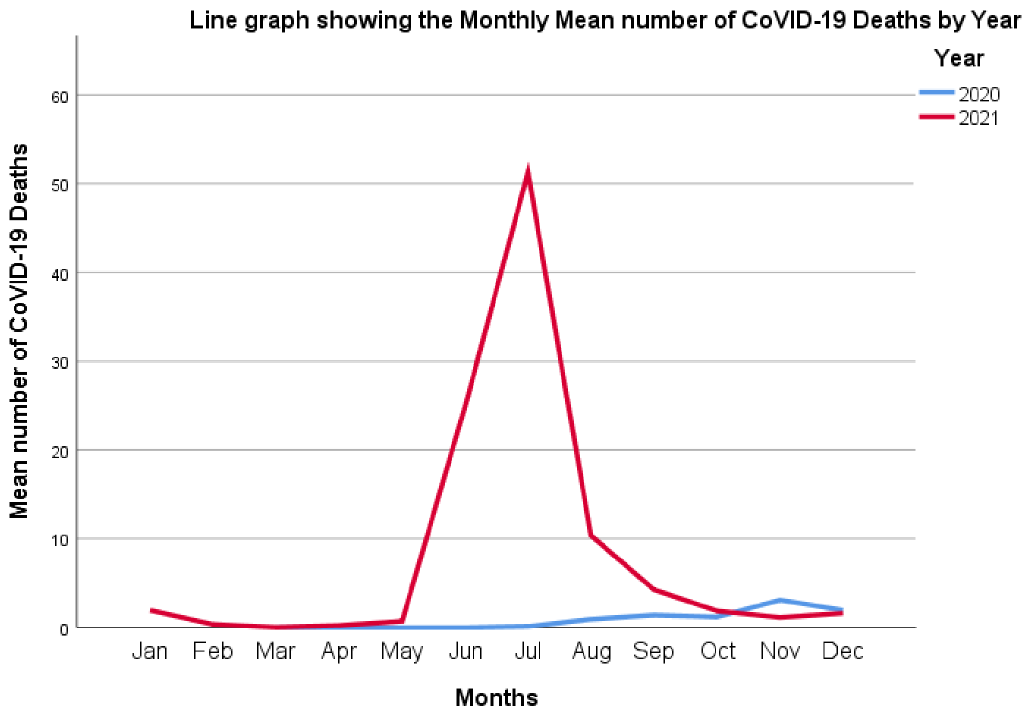
Figure 1: A line graph showing the monthly trend of COVID-19 cases by year



Trends of COVID-19 deaths

The mean monthly COVID-19 death increased slowly from July to November 2020 with about 5 people dying per the month of November 2020. Similarly, to the trend of COVID-19 cases in 2021, the COVID-19 deaths exponentially increased from May to a peak of 50 mortalities per July 2021 and exponentially decreased to about 10 mortalities in Between1. In between August and December 2021, the mean monthly deaths then gradually decreased to less than 10.

Figure 2: graph showing the monthly trend of COVID-19 deaths by year



Bivariate analysis of climatic determinants on COVID-19 cases in Uganda

From table 2; for a unit increase in the daily maximum temperature, the number of COVID-19 cases increased at 22.57 times [(95%CI =13.08-32.05), p-value <0.001]. Also, a unit increase in the daily temperature range, COVID-19 cases increased at 27.81 times [(95%CI = 17.60-38.01), p-value <0.001]. Furthermore, for a unit increase in daily relative humidity, the COVID-19 cases decreased at 7.74 times [95%CI = -10.20-(-5.28)), p-value <0.001]. Similarly, for a unit increase in the daily rainfall amount, the COVID-19 cases decreased at 9.60 times [95%CI = -14.70-(-4.44)), p-value <0.001]. Furthermore, for a unit increase in the daily average wind speed, the number of COVID-19 cases increased by 49.82 time [95%CI = 21.71-77.93), p-value 0.001].

Table 2; Showing the bivariate relationship between climatic determinants and COVID-19 cases in Uganda

Variable	Coefficient.	95%CI	P-value	R^2	RMSE
Temp. Max	22.57	13.08-32.05	<0.001	0.0311	325.29
Temp. Min	-4.237	-22.36-13.88	0.646	0.0003	330.43

Temp. Range	27.81	17.60-38.01	<0.001	0.0390	323.75
RHM	-7.74	-10.20-(-5.28)	<0.001	0.0530	321.55
Rainfall	-9.60	-14.70-(-4.44)	<0.001	0.0190	327.27
Surface pressure	144.74	-38.84-328.34	0.122	0.0020	329.90
Wind speed (Average)	49.82	21.71-77.93	0.001	0.0161	327.57
Wind speed (Max)	35.59	18.10-53.08	<0.001	0.0215	326.67
Wind speed (Min)	32.66	1.16-64.15	0.042	0.0040	329.47

RHM-Relative Humidity

Multivariate analysis of climatic determinants on COVID-19 cases in Uganda

From table 3: For a unit increase in the daily Maximum temperature, COVID-19 cases decreased by 43.31 times [95%CI = -71.87-(-14.76), p-value 0.003]. On contrary for the unit increase in the daily temperature range, the number of COVID-19 cases increased by 13.44 times [95%CI = -8.82-(-35.71), p-value 0.236]. Furthermore, for a unit increase in the daily relative humidity, the number of COVID-19 cases decreased by 17.72 times [95%CI = -21.07-(-8.37), p-value <0.001]. Also, for a unit increase in the daily temperature rainfall amounts, the number of COVID-19 cases decreased by 2.25 times [95%CI = -7.98-3.48, p-value 0.441]. In addition, for a unit increase in the daily average wind speed, the number of COVID-19 cases increased by 25.79 times [95%CI = -5.99-57.57, p-value 0.112].

Table 3; shows the multivariate relationship between climatic determinants and COVID-19 cases in Uganda

Variable	**Coef.**	**95%CI**	**P-value**	**R^2**	**RMSE**
Temp_Max	-43.31	-71.87-(-14.76)	0.003		
Temp_Range	13.44	-8.82-35.71	0.236		
RHM	-14.72	-21.07-(-8.37)	<0.001	0.06	318.84
Rainfall	-2.25	-7.98-3.48	0.441		
Windspeed (avg)	25.79	-5.99-57.57	0.112		

Bivariate analysis of climatic determinants on COVID-19 deaths in Uganda

Table 4; shows the bivariate relationship between climatic determinants and COVID-19 deaths in Uganda

Variable	Coef.	95%CI	P-value	R^2	RMSE
Temp_Max	0.597	-0.316-1.511	0.200	0.0009	31.390
Temp_Min	-2.711	-4.42-(-1.001)	0.002	0.0126	31.172
Temp_Range	1.594	0.612-2.577	0.001	0.0130	31.161
RHM	-0.228	-0.46-0.011	0.062	0.0037	31.313
Rainfall	-0.373	-0.86-0.120	0.138	0.0018	31.342
Surface pressure	33.32	16.03-50.61	<0.001	0.0192	31.068
Windspeed (Avg)	1.476	-1.21-4.16	0.282	0.0020	31.366
Windspeed (Max)	0.440	-1.24-2.12	0.607	-0.0011	31.387
Windspeed (Min)	2.63	-0.36-5.62	0.085	0.0029	31.325

From table 4; For a unit increase in the daily maximum temperature, the number of COVID-19 deaths increased by 0.59 times [(95%CI =-0.316-1.511), p-value 0.200]. Also, a unit increase in the daily temperature range, COVID-19 deaths increased at 1.59 times [(95%CI = 0.612-2.577), p-value 0.001]. Furthermore, for a unit increase in daily relative humidity, the COVID-19 deaths decreased at 0.228 times [95%CI = -0.46-0.011), p-value 0.062]. similarly, for a unit increase in the daily rainfall amount, the COVID-19 deaths decreased by 0.373 times [95%CI = -0.86-0.120, p-value 0.138]. Furthermore, for a unit increase in the daily average wind speed, the number of COVID-19 cases increased by 1.476 times [95%CI = -1.21-4.16), p-value 0.282].

Multivariate analysis of climatic determinants on COVID-19 deaths in Uganda

Table 5; shows the multivariate relationship between climatic determinants and COVID-19 deaths in Uganda

Variable	Coef.	95%CI	P-value	R^2	RMSE
Temp_Max	-4.47	-7.25-(-1.70)	0.002		
Temp_Range	4.36	2.197-6.527	<0.001		
RHM	-0.51	-1.135-0.099	0.100	0.02	30.99

Rainfall	0.53	-0.504-0.610	0.852
Windspeed (avg)	-1.85	-4.94-1.23	0.240

From table 5: For a unit increase in the daily Maximum temperature, COVID-19 deaths decreased by 4.47 times [95%CI = -7.25-(-1.70), p-value 0.002]. On contrary for the unit increase in the daily temperature range, the number of COVID-19 deaths increased by 4.36 times [95%CI = 2.197-6.527), p-value <0.001]. Furthermore, for a unit increase in the daily relative humidity, the number of COVID-19 deaths decreased by 0.51 times [95%CI = -1.135-0.099, p-value 0.100]. Also, for a unit increase in the daily temperature rainfall amounts, the number of COVID-19 deaths increased by 0.53 times [95%CI = -0.504-0.610, p-value 0.852]. In addition, for a unit increase in the daily average wind speed, the number of COVID-19 deaths decreased by 1.85 times [95%CI = -4.94-1.23, p-value 0.240]

SIMULATIONS

Every vaccine has different level of efficacy. We assume that the vaccine efficacy impacts disease spread and prevents transmission at the same rate, which is a reasonable assumption for our study. If people are vaccinated with the same vaccine type / brand, it is possible to introduce the efficacy of the vaccine in the model. We have made the following assumptions, which may not be true for all vaccines;

Only individuals belonging to the class *S* (susceptible) have been vaccinated. This is not included in the model.

The vaccine is an imperfect vaccine and can only reduce the chances of Covid 19 infections. Susceptible individuals that have been vaccinated however still stand a chance of infection, but it is less likely for the vaccinated individuals to be infected.

Individuals that recover become immune to infection.

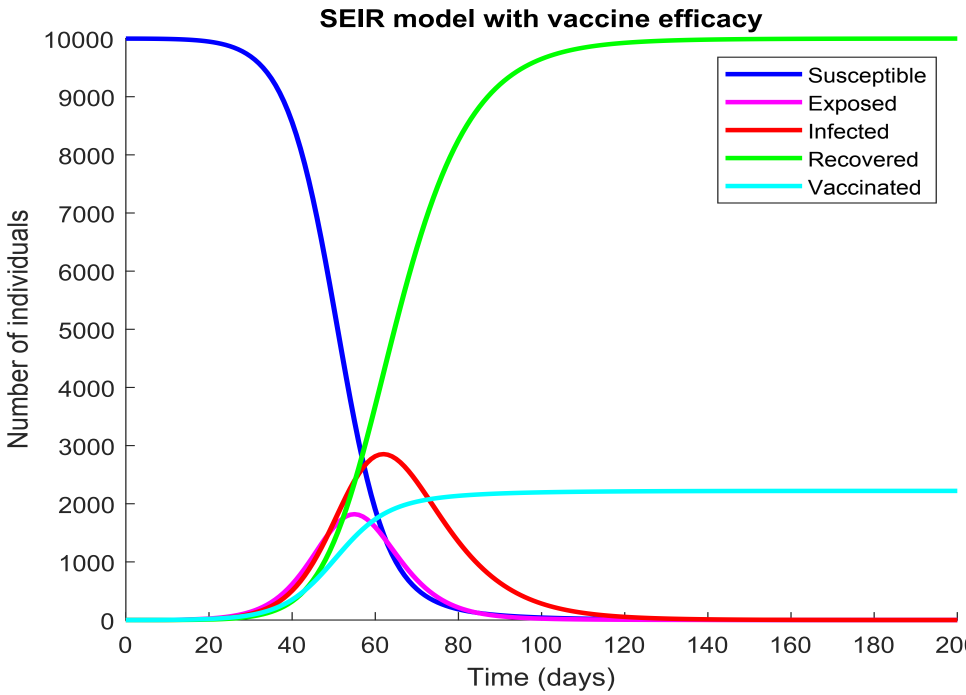


Figure 3: A graph showing the prevalence of Covid-19 with vaccination of susceptible individuals

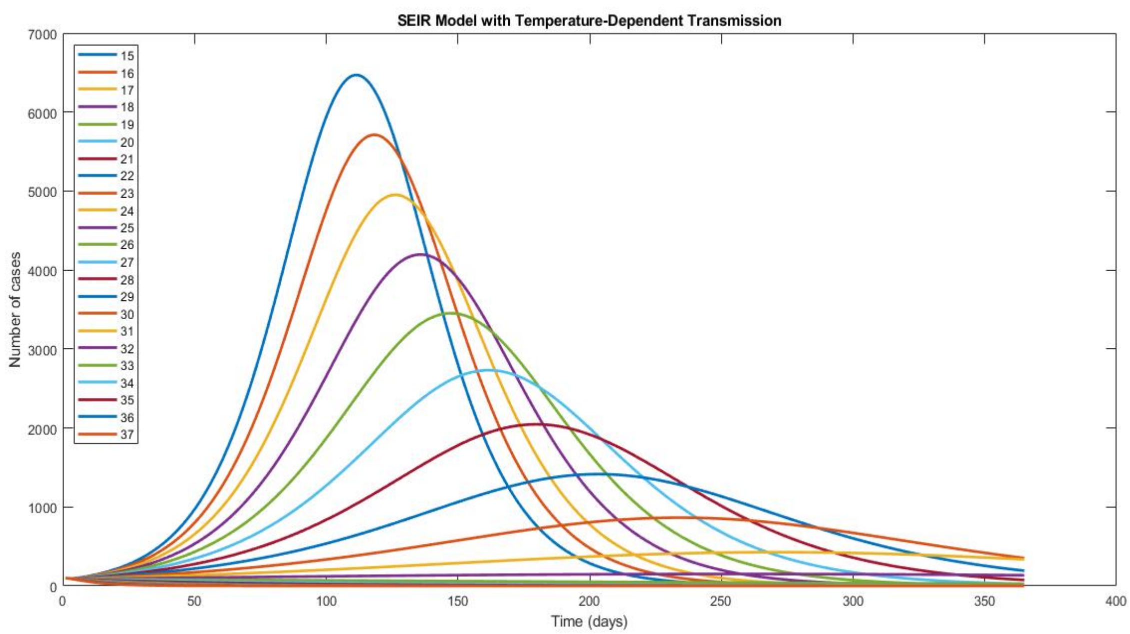


Figure 4: A graph of how Covid-19 cases vary with changing Temperatures throughout the year. The color code shows temperatures varying from 15-37 degrees Celsius throughout the year.

The graphs show that COVID-19 prevalence is high at very low temperatures and high low at very high temperatures. Furthermore, it is observed that in the presence of vaccination, the prevalence of COVID-19 is low. The research showed theoretical results on the impact of a vaccine in slowing the spread of the virus through epidemiology. We used an *SEIR* deterministic compartment model to analyze the spread of the virus. Additionally, a vaccine compartment was added into the *SEIR* model (e.g. *SEIR* with vaccine model) with the hypothesis that the vaccine is imperfect to see how a vaccine would change the dynamics of the whole system. We see improvement in lowering the number of cases of COVID-19 when people are vaccinated.

The susceptible individuals of the *SEIR* model, $S^0 = \frac{\Lambda}{\mu}$, are reduced to $S_v^0 = \frac{\Lambda}{\eta + \mu}$. In other words, susceptible that are vaccinated are assumed to move to the vaccine compartment. Although vaccinated individuals are still able to contract the virus, they occur at reduced rates of $(1-\varepsilon_v)\beta_1$ and $(1-\varepsilon_v)\beta_2$. This shows it is less likely for the vaccinated individuals to be infected. Thus, it helps lower the number of cases moving from the *S* compartment to the *E* compartment and potentially becoming infectious.

DISCUSSION

From the present study, it is evident that the COVID-19 cases per 100,000 have been disproportionate across the different districts of the country. This further revealed the epidemiological burden of COVID-19 disease within the study period as smaller and larger districts are closely compared with strong considerations to cases per 100,000 members of the population. It is thus imperative to not a majority of the districts (Amuru, Gulu, Moroto, Mbarara) that presented with high case/100,000 were not highly populated with population sizes of 222,000, 334,500, 121,200 and 407,641 respectively. Similarly, a majority of the districts (Alebtong, Kyegegwa, and Kakumiro) that presented with lower COVID-19 cases/100,000 were to some extent highly populated with population sizes of 272,000, 475,600 and 513,200 respectively. This implies that the observed case/100,000 in the respective districts could have been attributed to influences in the variability of weather elements.

The findings from the present study reveals a strong ambi-directional relationship between temperature and COVID-19 cases. Specifically, increase in high temperatures (daily maximum temperature) was positively associated with the increase in the COVID-19 cases. This could be attributed to the fact that higher temperatures exercabated profound activities among the susceptible host and hence making them come in contact with the pathogen and thus the increase numbers in disease cases. The findings of the present study are in agreement with the findings of a study conducted by Bashir *et al.* (2020), who found a 3 pm daily temperature increase in the COVID-19 cases much as their study only looked at data for COVID cases and weather elements within only 3 months (January to March 2020).

Still linked to temperature, in study the daily minimum temperature was negative correlated to the increase in the cases of COVID-19. This particular finding is as well consistent with the finding of (sobral *et al.,*) who found that lower temperatures increase the incidences of COVID-19 cases. The low and high daily temperatures bi-directional relationship with COVID-19 cases confirms the complexity and heterogeneity of SARs-COV-2 across the landscape in the different countries/regions and even hemispheres.

Furthermore, this study reveals an inverse relationship between relative humidity and COVID-19. This could be attributed to the fact that a lower amount of water vapors in the atmosphere favors the survival of the SARs-COV-2 pathogen than the high amount of water vapors. The present finding is thus like the study conducted by Bashir *et al.,* who found out that stated that lower relative humidity was associated with increased occurrence of COVID-19 cases; and that a reduction in relative humidity of 1% was predicted to be associated with an increase COVID-19 cases by 6.11%.

The present study reveals that an increase in the rainfall amounts led to a decrease in the number of COVID-19 cases. This inverse relationship could have been attributed to the fact high amounts of rainfall provides unfavorable conditions for the survival of the SARs-COV-2 pathogen. The finding could also be attributed to fact that rainy climatic conditions limits the movements of contact, keeps them confined to one place (Home) and as such reduces on the transmission of the virus. The finding of this study is thus similar to the finding of a study conducted in Pakistan by Bashire at al., who found that the correlation between COVID-19 cases and rainfall was negative much as the association was statistically significant.

Conclusion

The present study reveals that different environmental weather parameters affected the deaths and cases of COVID-19. Increase in the daily maximum temperature resulted in the decrease of COVID-19 cases and deaths. Increase in the daily relative humidity resulted in to decrease of COVID-19 cases and deaths. Specifically, increase in the daily rainfall amounts resulted in to decrease and increase in the number of COVID-19 cases and deaths respectively. The same trend was exhibited by the daily windspeed.

Our study acknowledges a limitation of using the secondary data whose quality depended greatly on the accuracy at which they were reported by the health workers from respective districts. In addition, generalizing the finding from this study is affected by the influence of lockdown and vaccination on the incidence and deaths due to COVID-19. Restrictions in the movements of the contacts as well as cases during the lockdown could have limited the transmission of the virus to the susceptible hosts in the community. Additionally, consideration of the sociodemographic characteristics of the victims involved could be investigated in relation to COVID-19 pandemic was not exploited due to the limitation in the data .

From our study we recommend, 1) More surveillance to be strengthened during the periods of April and August. 2) Much surveillance needs to be instituted in the districts that presented with the higher number of cases and deaths. And 3) scientific research studies be focusing on the molecular adaptation mechanisms of the SARs-COV-2 pathogens to the changing environment weather parameters be conducted.

Author Contributions

JO: Conceptualization, initial writing, data analysis, final writing
LN: Conceptualization, Supervision
MJ: Conceptualization initial writing
CK: Data analysis, final writing
GS: Data Analysis, initial writing
OFL: Ideation, proof reading
KGB: Data accesses from the Ministry Health, review
MD: Data accesses from the Ministry Health, review
AMP: Review and proof reading
MM: Supervision and proof reading

CK: Supervison, conceptualization, review

LT: Critique, Proof reading and guidance

Ethical considerations

Clearance for this research was sought from the Research Ethics Committee (REC) at the School of Biosecurity, Biotechnical and Laboratory Sciences (SBLS) reference number 2020/HD17/22031U. Also further approval was obtained from the Uganda National Council of science and technology with approval number SS1482ES. In upholding ethics during data collection, we obtained official permission to access the database from concerned at both Ministry of Health and Meteorological Centre.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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