Spatial and Spatio-temporal Epidemiology 37 (2021) 100416

Contents lists available at ScienceDirect

Spatial and Spatio-temporal Epidemiology

journal homepage: www.elsevier.com/locate/sste

COVID-19 modelling in the Caribbean: Spatial and statistical assessments

Stephan Moonsammy[a,*], Temitope D. Timothy Oyedotun[b,*], Donna-Marie Renn-Moonsammy[d], Temitayo Deborah Oyedotun[c]

[a] *Department of Environmental Studies, University of Guyana, P. O. Box 10 1110, Turkeyen Campus, Greater Georgetown, Guyana*
[b] *Department of Geography, University of Guyana, P. O. Box 10 1110, Turkeyen Campus, Greater Georgetown, Guyana*
[c] *Faculty of Earth and Environmental Sciences, Faculty of Humanities and Education, University of Guyana, P. O. Box 10 1110, Turkeyen Campus, Greater Georgetown, Guyana*
[d] *Pensa Fuori Concepts, #4 ParakeetStreet, Trincity, Trinidad and Tobago*

ARTICLE INFO

Article history:
Received 1 October 2020
Revised 17 December 2020
Accepted 2 March 2021
Available online 6 March 2021

Keywords:
Caribbean
COVID-19 cases
COVID-19 deaths
Spatial variation

ABSTRACT

The novel COVID-19 disease has highlighted the vulnerability of small and developing economies in managing what is now a global health crisis. This study presents the preliminary overview of the dynamics of the spread and expansion of COVID-19 as the disease takes its footprint in the Caribbean. The study explored the spatial clusters of the disease and its variations in the Caribbean region. Data was gathered from the World Health Organization reports and collated into a cross sectional data set. Spatial mapping and spatial lag analysis were conducted to identify spread patterns and statistical relationships with several relevant socioeconomic variables. Models showed the prominence of cases and deaths in the Caribbean region have a spatial connection with mainland countries. The models also show the connection between COVID-19 cases and deaths and the availability of medical services within the country. Results also showed similar social distancing policies adopted in the region and the possible connection between prevalence of diabetes and hypertension regionally impacted the number of deaths. It is hoped that the findings presented here will be useful in planning for an epidemiological response for the region based on the differences in the patterns for possible interventions and actions.

1. Introduction

In December 2019, the novel SARS-CoV-2 commonly known as the corona virus (COVID-19) was first reported to the World Health Organization (WHO) from the initial outbreak in Wuhan China. Since then, the virus had spread at an exponential rate globally within a three-month time period with the WHO declaring it a global pandemic in February 2020 (WHO, 2020). To date (as of 12:24 am CEST, 30 November 2020), COVID-19 has spread to 212 countries and territories globally with an estimated 71 million confirmed cases and over 1.6 million deaths globally,[1] making it the most severe pandemic since the Spanish Flu in the 1900s. The emergence of COVID-19 has revealed an underwhelming response by health authorities in containing the initial stages of its spread and the shortcomings of several of the public health institutions globally in dealing with a wide scale pandemic. The pandemic epicentre has shifted from China to Italy and then, the United States in the first three months and has now rampant cases in India and Brazil as well. Of particular interest to scientist is the first shift of the epicentre from China to Italy, as scientist are fully unable to explain a reason for this shift since China is not directly connected to Italy and Italy was not the first country in Europe to record a case (Giordano et al., 2020; Guiliani et al., 2020; Rothe et al., 2020). Epidemiological evidence has attributed the rampant spread of COVID-19 globally to its severity as a contagion via human to human transmission spread by airborne vectors, contact with infected individuals, and the virus capacity to survive in the external environment for many hours (Guan et al., 2020; Liu et al., 2020). In addition to its epidemiological characteristics, the global movement of people and congested urban cities are the other main contributing factors resulting in the current spread of the disease to date (Chinazzi et al., 2020).

* Corresponding authors.
E-mail addresses: stephan.moonsammy@uog.edu.gy, stephan.antonio.tt@gmail.com (S. Moonsammy), temitope.oyedotun@uog.edu.gy, oyedotuntim@yahoo.com (T.D.T. Oyedotun).

[1] For full compilation of COVID-19 related data and reports, see - https://covid19.who.int/; and https://www.worldometers.info/coronavirus/ Accessed on 30 November 2020.

https://doi.org/10.1016/j.sste.2021.100416
1877-5845/

In unravelling the complexities of COVID-19 spread globally, spatial and temporal models were developed to account for the phenomenological outliers of the virus transmission. The rapid changes in the disease epicenters with concurring spread to neighbouring regions and territories suggest that spatial factors might play an important role in the number of cases and deaths from COVID-19 (Tobler, 2020). Consequently, spatial and temporal models have been developed to account for variations in the pattern of virus transmission. Guiliani et al. (2020) attempted to model and predict the spatial diffusion of the number of COVID-19 cases and forecast where and when the disease will occur in Italy. Sardokie and Owusu (2020), presented several spatial fixed effects models on attributable deaths and confirmed cases in mainland China in order to establish linearity between deaths and cases. Adekunle et al. (2020) further expanded on the work of Sardokie and Owusu (2020) by extending and modifying spatial models to explore the linearity of attributable deaths and confirmed cases for the African continent. Scientific research on COVID-19 is tackling the pandemic on several fronts.

While the global priority is to find a vaccine, scientists are also using this crisis to explore our vulnerabilities to prevent similar events. Fanelli and Piazza (2020) conducted temporal modelling with data from China and Italy to forecast future outbreaks in an effort to provide the health sector with advanced warning for better preparation. Another key area needing further investigating is how socio-economic factors are impacting the COVID-19 spread. Studies have demonstrated that economic centres, international travel and social gatherings are the primary factors that facilitate human to human transmission. Chinazzi et al. (2019) uncovered an 80% decrease in cases due to the imposition of travel bans. Rodriguez-Morales et al. (2020) identified the vulnerability of the populated cities in Brazil and the spatial impacts to neighbouring countries because of the economic connections of Brazil in South America.

To date, there are few studies that explore the relationship between the spread of COVID-19 and socio-economic factors, but more efforts are being made to assess its spread over spatial regions (See Adekunle et al., 2020). Publish reports on COVID-19 and its associated socio-economic factors in the region have focused predominantly on countries in Latin America (Oyedotun and Moonsammy, 2000; Rodriguez-Morales et al., 2020; Zhang et al., 2020) but few studies looking at the Caribbean context are emerging (Murphy et al., 2020).

Overall the Caribbean governments have made great strides in prevention and slowing the rate of spread of the disease through its populations (Burki, 2020; Candido et al., 2020; Zhang et al., 2020). According to World Health Organization reports, there are confirmed cases in every country in Latin America and the Caribbean. WHO has confirmed over 8000,000 cases in the region with the spread likely originating from the United States of America. Brazil has the most reported cases and deaths in the region with its first reported case in February 26th, 2020 (Oyedotun and Moonsammy 2020).

The literature outlined show three key features of COVID-19 modelling in regional studies that guides the development of this study. Firstly, the functional form of the structural models provides adequate model estimates when a linear approach is implemented. Adekunle et al. (2020) and Sardokie and Owusu (2020), adopted a linear functional form and demonstrated model diagnostics that showed unbiased estimators. Secondly, as research continues to explore the factors perpetuating the continued expansion of COVID-19, researchers have recognized the importance of understanding the spatial dimension and thus spatial models are often used in explaining and predicting COVID-19 trajectories. Guiliani et al. (2020) highlighted that spatial modelling of COVID-19 can greatly improve the estimation of cases and deaths which can aid and inform policy makers in improving public health management. Finally, the rate of infections and contagious spread is a focal area of research that is still in its infancy, as more research is needed on the many pathways of infection that may exist from the multiple social dimensions within countries. The factors of economic activity, public health spending, the movement of people and the restrictive measures are a few broad areas within society that can be explored to understand the spread of COVID-19. Several studies have attempted to explore these dimensions to firmly establish an empirical linkage between them and COVID-19 spread (Candido et al., 2020; Chinazzi et al., 2020; Zhang et al., 2020). Research focused on the social dimensions of COVID-19 spread will not only help in the management of COVID-19 but also inform on potential areas to focus intervention in the lieu of a similar event in the future. This manuscript reports the development of a spatial model that focuses on exploring the relationships between COVID-19 cases and related deaths and various socio-economic factors from a Caribbean perspective. In so doing it shall add to the growing literature on COVID-19 and its impacts in smaller and vulnerable economies and contribute to better understand some of the underlying social factors perpetuating the spread of the disease in the Caribbean.

2. Materials and methods

2.1. Data collection and synthesis

Three secondary data sources were used in this study namely, World Health Organization (WHO) COVID-19 reports for the Caribbean, Gap Minder - and World Banks's Development Indicator's databases. The COVID-19 data for the Caribbean was acquired from the World Health Organization (WHO) reports.[2] COVID-19 reports for the Caribbean included cumulative number of confirmed cases and deaths recorded from 14 February to 30 November 2020. The data gathered is based on real time information as such, the data used can be considered a census for COVID-19 in the Caribbean. Additionally, data on population density, health expenditure and per capita gross domestic production (GDP/capita) were sourced from Gap Minder.[3] We also obtained data on number of physicians and the number of hospital beds per thousand for each of the countries from the World Banks's development indicator's database.[4] Additionally, the grey literature which include government briefs from the Caribbean, the Pan-American Health Organization (PAHO) reports and country based health and management projects were also searched to gather data on the national prevalence of diabetes and hypertension, the restrictions, policies and quarantine measures the Caribbean adopted.

The data on COVID-19 was aggregated for each of the Caribbean countries observed. For each of the socio-economic variables identified, observations for 2020 were recorded. The exogenous variables used in the model were from data sourced as a combination of annual values for each Caribbean country (population density, annual health care expenditure, per capita income, national rates for non-communicable diseases, etc.), qualitative measures of the policies adopted for COVID-19 in the country (border closures, social distancing measures etc.) and spatial aspects (travel bubbles, land and sea bridges, air bridges, etc.). The study adopted a cross sectional analytical technique as the models attempted to demonstrate the current circumstances in each Caribbean country and the connection between the current accumulation of COVID-19 cases and deaths and the exogenous variables. Cross-sectional analysis

[2] https://covid19.who.int/ - Accessed on 30 November 2020.

[3] https://gapminder.org. Accessed on 20 June 2020.

[4] https://databank.worldbank.org/source/health-nutrition-and-population-statistics - Accessed on 20 June 2020.

to model the influence of social factors on COVID-19 cases and deaths is well documented in the literature (Murphy et al., 2020; Nguimkeu and Tadadjeu, 2021; Saqlain et al., 2020).

2.2. Spatial mapping

The shapefile data used for spatial mapping and representation of the phenomena in this paper was extracted from the database for Global Administrative Areas (GADM database) version 3.6 of 2018.[5] The georeferenced shapefile datasets for each of the countries were downloaded, extracted, merged and linked with the attribute data (e.g. confirmed cases, attributable deaths, physicians per thousand, etc.) for the countries in the Environmental Systems Research Institute Geographical Information System (ESRI©ArcGIS 10.6.1). We utilised exploratory spatial analysis to investigate and present a spatial variation and distribution of the occurrences of COVID-19 cases and healthcare capacities (physicians per thousand, which include generalists and specialist medical practitioners) across the Caribbean. Specifically, we utilised the spatial capabilities in GIS to visualise the COVID-19 case and death counts on maps and display them based on different administrative boundaries. We used this GIS capabilities to identify the hotspot concentration of confirmed cases or deaths in the Caribbean regions.

2.3. Model structure

Our empirical intentions were to explore how social factors including demographics, economic outlook and national policies on COVID-19 has impacted its spread as measured by the number of cases and deaths in the Caribbean. We adopted a linear approach assuming strict exogeneity amongst the explanatory variables. A linear approach was outlined by several studies, as the literature shows the variations in COVID-19 cases deaths and cases fits a linear structural model best when regressed against various exogenous variables (Adekunle et al., 2020; Nguimkeu and Tadadjeu, 2021; Ogundokun et al., 2020; Rath et al., 2020; Sardokie and Owusu, 2020). The functional relationship is expressed as:

$$\mathrm{Y_{iN}} = \int (\mathrm{X_1}, \mathrm{X2}, \ldots.., \mathrm{XiN}) \tag{1}$$

where $\mathrm{Y_{iN}}$ are the dependant variables related to aggregated COVID-19 cases and deaths for the individual countries (i) for the total number of countries observed in the dataset (N) and $\mathrm{X_1,X_2,\ldots\ldots,X_{iN}}$ are independent exogenous variables for the ith country in the total number of countries (N). In analysing the data, classic linear regression models were adopted using a linear functional form:

$$\sum Covid-19Deaths_{iN} = \alpha + \beta ln \sum CovidCases_{iN} + \beta lnX_{iN} + \beta D_i + e_{i,} \tag{2}$$

where $\Sigma Covid\text{-}19Deaths_{iN\ is}$ the sum of COVID-19 related deaths in the individual country (i), $\Sigma CovidCases_{iN}$ is the sum of confirmed COVID-19 cases in the individual country (i), X_{iN} is a vector of exogenous socio-economic variables for the individual country (i), D_{i} represent a vector of intercept dummy variables for country (i), α and β are the constant and coefficient parameters and $e_{\mathrm{i},}$ is the error term. Eq. (2) also expands upon the models done prior looking at the linearity relationship between attributable deaths and confirmed cases of COVID-19 (Adekunle et al., 2020; Sarkodie and Owusu, 2020). In addition to the model expressing the attributable deaths as a dependant variable, a model was also developed looking at factors that can affect confirmed cases. A semi-log or log-lin functional form was used an expressed as:

$$\mathrm{In} \sum CovidCases_{iN} = \alpha + \beta X_{iN} + \beta D_i + e_i, \tag{3}$$

The classic linear models are often implemented to model infectious diseases (Matas et al., 2013; Szmaragd et al., 2006). In this study, the linear models adopted included a spatial and non-spatial aspect. Analysing the spatial aspect, spatial lag models were implemented.

$$\sum Covid-19Deaths_{iN} = \alpha + \delta WCOVID-19Deaths_{iN-1} + \beta \sum CovidCases_{iN} + \beta X_{iN} + \beta D_i + e_i \tag{4}$$

$$\mathrm{In} \sum CovidCases_{iN} = \alpha + \delta W \sum CovidCases_{iN} + \beta X_{iN} + \beta D_i + e_i, \tag{5}$$

where $\delta WCOVID\text{-}19Deaths_{\mathrm{iN\text{-}1}}$ and $\delta W\Sigma CovidCases_{iN}$ represents a spatial lag variable of the dependant variables for eqns. (4) and (5). The spatial lag is a weighted average of attributable deaths and confirmed cases of Caribbean countries that have direct travel routes with each other. Travel routes were deemed as a relevant variable as the literature on COVID-19 indicated the prominence of travel routes in spreading the virus. Even though a standardized spatial lag is preferred, a differential lag was used given the inconsistency of travel routes amongst the Caribbean countries.

3. Results and discussions

3.1. Preliminary COVID-19 cases, deaths and distributions in the Caribbean

The spatial distribution of the current state of COVID-19, the total number of attributable deaths from COVID-19 (as of the 30 November 2020), the generalist and specialist medical practitioners (physicians) per thousand of the population per country in the Caribbean are presented in Fig. 1 (A – C). The figures show that cases of COVID-19 varied spatially across the Caribbean with notably high incidences of the virus infection in Dominican Republic, followed by Jamaica, Haiti and Cuba respectively (Fig. 1A). The mortality rate from COVID-19 in the Caribbean is highest in the Dominican Republic, followed by Jamaica, Haiti and Bahamas respectively (Fig. 1B). However, when the percentage incidence of confirmed and reported cases were compared with the population, the Bahamas, Belize, the Dominican Republic, Suriname, Guyana, Trinidad & Tobago, and Cayman Islands had the highest percentage of incidence per population (Fig. 4). Within the Caribbean, Cuba had the highest rate of physicians (doctors) per thousand of the population at 8.3, followed by Trinidad and Tobago at 4.2 and St Kitts and Nevis at 2.8 respectively (Fig. 1B). Countries in the Caribbean with the lowest rates of physicians per thousand of the population include Haiti at 0.2, Saint Lucia at 0.6, and Guyana at 0.8. Dominica, Belize, Suriname, Jamaica, Grenada and the Dominican Republic have rates between 1.1 and 1.4 respectively. The Dominican Republic, Haiti, Guyana, Jamaica and Suriname also reported higher mortality rates within the Caribbean in that order (Fig. 4).

The summarized report overviewing the occurrence of COVID-19 in the Caribbean countries are presented in Table 1. This covers the timeline when it was first reported in Dominican Republic from 2nd March 2020 – 30th November 2020 (the date of this study). As evident from Fig. 2, the COVID-19 outbreak does not occur evenly nor spread evenly across the Caribbean per three-months of occurrence. The results show that during the first three months of March-May 2020, the Dominican Republic had the highest record of pandemic cases followed by Cuba and Haiti. Within

[5] https://gadmn.org./data.html - Accessed on 20 June 2020.

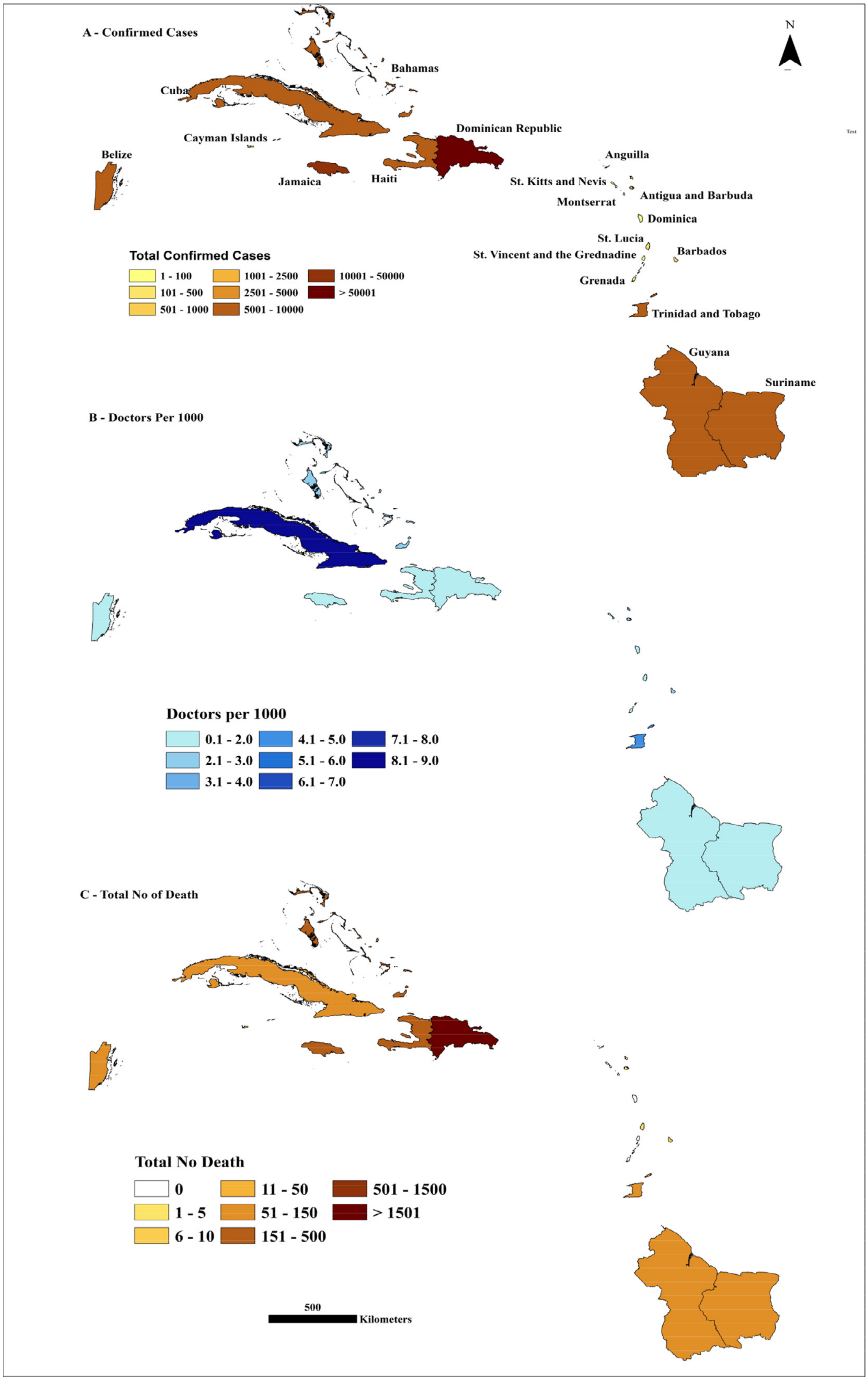


Fig. 1. (A) Total number of confirmed COVID-19 cases as at 30 November 2020; (B) Distribution of number of medical doctors/physicians per 1000 across the Caribbean; and (C) Total number of COVID-19 death cases as at 30 November 2020 across the Caribbean.

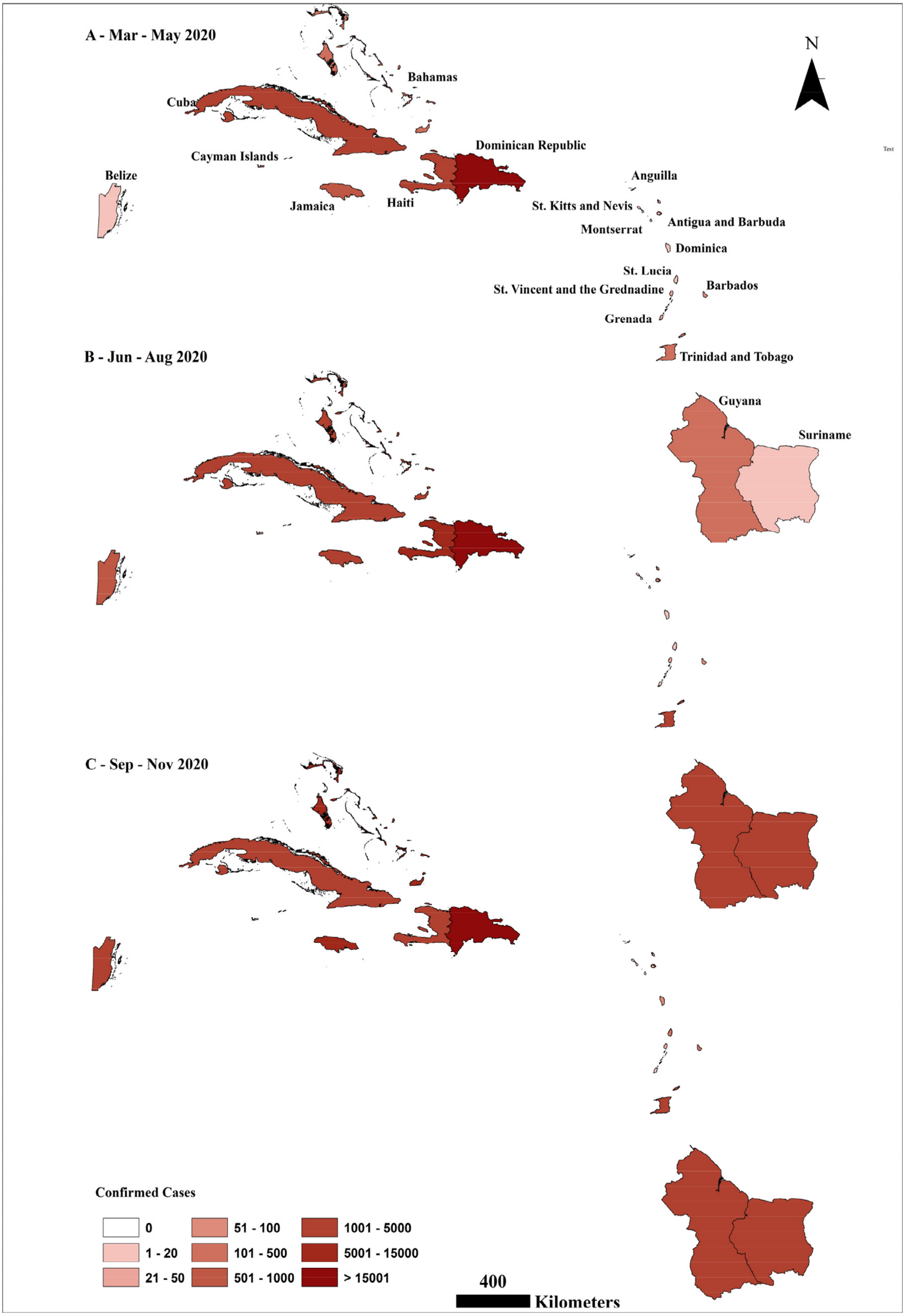


Fig. 2. Spatiotemporal number of confirmed cases of COVID-19 in the Caribbean (A) March to May 2020 cases; (B) June - August 2020 cases; and, (C) September to November 2020 cases.

Table 1
Synthesis of COVID-19 cases and death in Caribbean as at 30 November 2020.

Country	Date and number of First Confirmed Case(s)	Date and number of the first death	Cumulative Confirmed cases as at 30 November 2020	Cumulative Number of Death as at 30 November 2020
Anguilla	26 March 2020 (2)	N/A	06	0
Antigua and Barbuda	13 March 2020 (1)	09 April 2020 (2)	143	4
Bahamas	17 March 2020 (1)	03 April 2020 (1)	7541	163
Barbados	18 March 2020 (2)	07 April 2020 (1)	278	7
Belize	24 March 2020 (1)	07 April (1)	5647	144
Cayman Islands	13 March 2020 (1)	16 March 2020 (1)	274	2
Cuba	13 March 2020 (4)	18 March 2020 (1)	8233	134
Dominica	24 March 2020 (2)	N/A	85	0
Dominican Republic	02 March 2020 (1)	17 March 2020 (1)	143,473	2330
Grenada	23 March 2020 (1)	N/A	41	0
Guyana	13 March 2020 (1)	13 March 2020 (1)	5338	149
Haiti	20 March 2020 (2)	07 April 2020 (1)	9272	232
Jamaica	10 March 2020 (1)	19 March 2020 (2)	10,709	256
Montserrat	18 March 2020 (1)	26 April 2020 (1)	13	1
Saint Kitts and Nevis	26 March 2020 (2)	N/A	22	0
Saint Lucia	15 March 2020 (2)	N/A	252	2
Saint Vincent and the Grenadines	13 March 2020 (1)	N/A	85	0
Suriname	15 March 2020 (1)	07 April 2020 (1)	5312	117
Trinidad and Tobago	13 March 2020 (1)	26 March 2020 (1)	6630	118

the next three months of June to August 2020, the Dominican Republic along with Haiti still had the highest number of pandemic cases followed by Suriname, Bahamas, Cuba and Trinidad & Tobago, while in Jamaica and Guyana, there were some noticeable rate of new cases occurring. By last three months of this study from September to November 2020, the Dominican Republic still maintained the record for the highest number of pandemic cases within the Caribbean, followed closely by Jamaica, Bahamas, Trinidad & Tobago, Belize, Cuba, Guyana and Suriname respectively (Fig. 3).

3.2. Spatial and non-spatial linear models

The empirical analysis adopted linear regression modelling using heteroskedasticity correction approaches. The exogenous variables used in the models were based on the dependant variables. For the models where the dependant variables were number of cases, variables were used looking at the factors that can inhibit or promote the spread of the virus. These variables included population demographics, social distancing policies developed for COVID-19 and spatial factors such as the land, marine and air bridges that exist between countries. For the models where the dependant variables were number of COVID-19 related deaths, then factors surrounding health care, prevalence of non-communicable diseases and expenditure in the health sector was adopted. Essentially, the rationale behind the structural models here is that not all factors can be related to both cases and deaths. For instance, the literature shows the rate of the non-communicable diseases will impact the number of deaths more than spreading new cases in the country (Hartmann-Boyce et al., 2020). Likewise, deaths from COVID-19 will be indirectly related too some of the spatial dimensions vis-à-vis the number of cases in the country.

For the models with the number of COVID-cases as the dependant variable, the exogenous variables used were, data on population density, per capita income (2011 prices), a dummy variable for countries that have a direct flight with the United States of America or Brazil which are two of the epicentres for the disease (Badr et al., 2020; Oyedotun and Moonsammy, 2020), a dummy variable for countries that have land and marine bridges with mainland America (North, Central and South America) and the spatial lag variables accounting for the movement of people between Caribbean countries. These variables were identified from the literature on COVID-19 which indicated the significance of travel routes between countries, crowded places and economic policies and activities affecting disease spread (Chinazzi et al., 2019; Kang et al., 2020). Additionally, the social distancing policy measures were also explored to see if there were any notable changes in the number of cases as a result of these policies. The initial findings in this study showed that all the countries in the Caribbean explored for this study adopted similar social distancing measures such as the closure of schools, closure of public places including restaurants, churches, recreational spaces and public sector offices in the initial stages of the pandemic and then a restricted opening of these institutions that limit the number of persons and activities at the later stages of the pandemic. These findings corroborated with the study done by Murphy et al. (2020) which found that the Caribbean region implemented similar social distancing measures generally in order to restrict the internal movement of persons. In an effort to restrict intercountry movement, all the Caribbean countries closed their airports in the month of March. Interestingly, some countries chose to resume air services at different stages of the pandemic. Some chose to open their airports and borders as early as three months after closing them while others still have their borders closed. Due to the differences in the policy approach with respect to the country's borders, a variable on the length of the border closure was included to assess the impacts this had on the spread of COVID-19 cases.

For the models with the number of COVID-19 related deaths as the dependant variable, the exogenous variables used were, data on the number of hospital beds per 1000 persons in the country, public and private health care expenditure, the prevalence of diabetes and hypertension as the literature shows the increased susceptibility of persons diagnosed with these conditions (Hartmann-Boyce et al., 2020) and the cumulative number of cases in the country as the prior literature attempted to establish the linearity between COVID-19 deaths and cases (Adekunle et al., 2020; Sardokie and Owusu, 2020). For the health measures adopted regionally in response to COVID-19, all the countries adopted the guidelines from the World Health Organization[6] in terms of public education on safety and sanitation, protocols for testing and diagnosing, isolating and quarantining confirmed cases, providing intensive care services for vulnerable groups and strict frontline worker protocols for staff dealing with COVID-19 patients.

[6] https://www.who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance

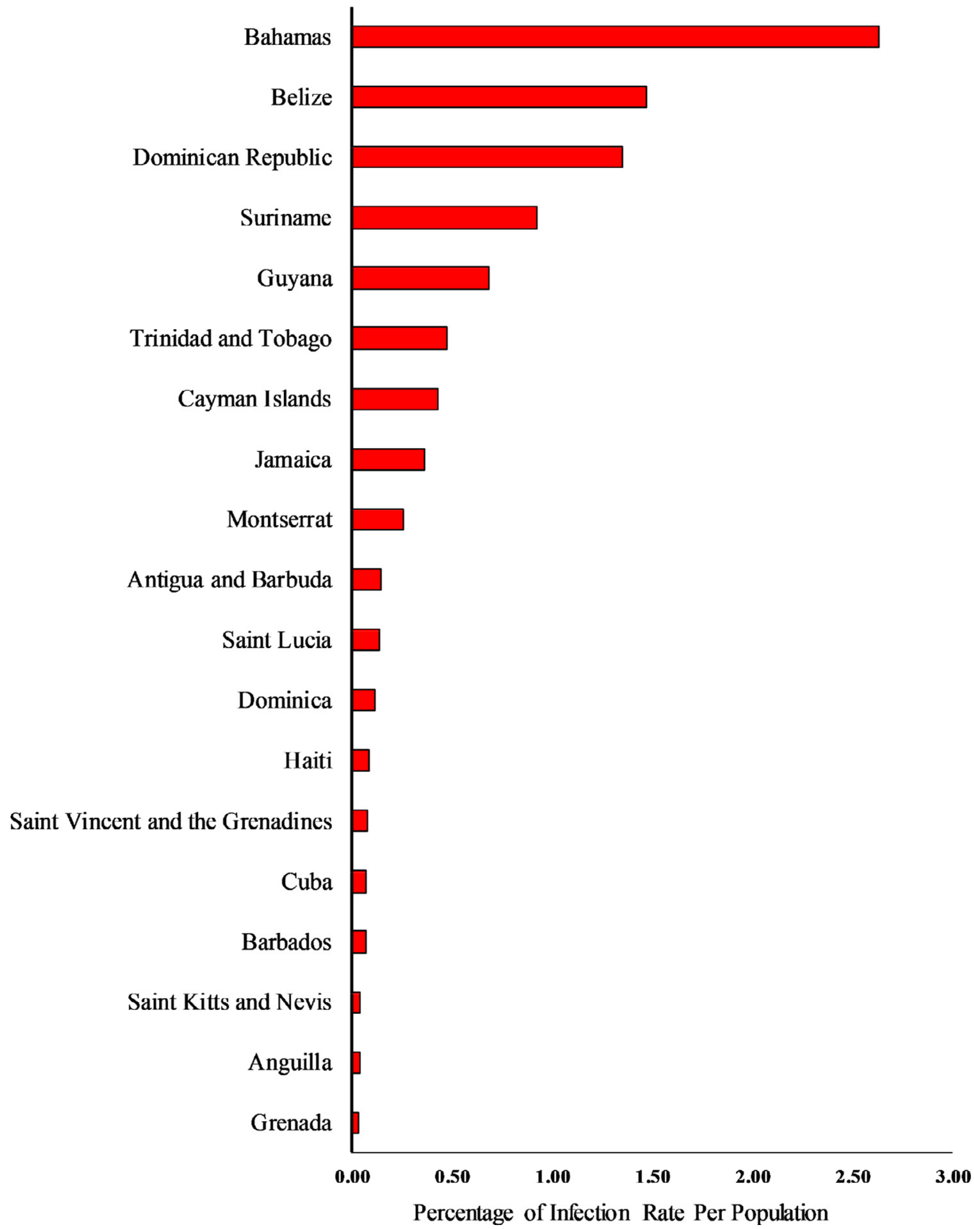
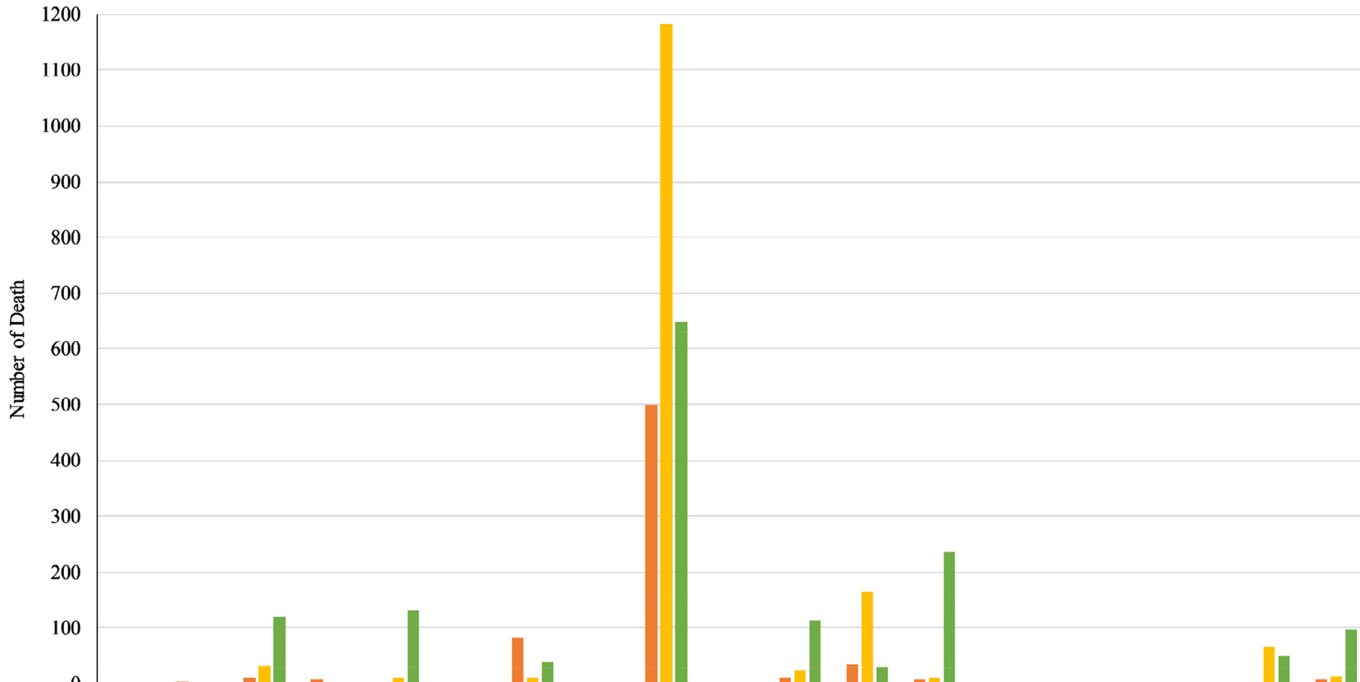


Fig. 3. Percentage of Infection Rate per Population (rate as at 30 November 2020).

The estimated parameter coefficients for all models were presented in table 2. Looking at the factors affecting COVID-19 cases, the models showed that at the current stage of the pandemic in the Caribbean, population density was an insignificant variable in the spread of COVID-19 cases. This finding is particularly interesting as the conventional findings in the literature showed population density as a significant factor (Bhadra et al., 2020; Kadi and Khelfaoui, 2020; Rocklöv and Sjödin, 2020). Both the spatial and non-spatial models for COVID-19 cases showed significant variables for per capita income (at 10% significance in both models), length of closure of the airport (at 1% in spatial model and 5% in non-spatial model) and if the country has a land and sea bridge with the main land (1% significance in both models). The spatial lag variables and the dummy variable for direct flights from a country declared as a COVID-19 epicentre (United States or Brazil) were insignificant.

Looking at the significant variables against the variables that were insignificant, a comprehensive picture on the spread of COVID-19 emerges for the Caribbean. Population density being insignificant in the Caribbean can be attributed to the high number of cases occurring in countries with low population densities such as Guyana and Suriname and low number of cases occurring in countries with high population densities such as Barbados and Grenada. Regionally, despite the most populous countries such as Dominican Republic, Cuba, Jamaica and Haiti having the highest number of cases, the population distribution is not an influencing factor in COVID-19 spread. The spread of COVID-19 in the Caribbean seems to be more influenced by the ease of people moving between countries as the models showed a positive significant relationship between COVID-19 cases and the country having a land or sea bridge with the mainland. Countries with a land and sea bridge with the main land Americas (North, Central and South) will experience 3.85 more cases than those without these bridges. This finding essentially shows the movement of people (most likely undocumented movement) is one of the main factors spreading COVID-19 in the Caribbean. Countries like the Bahamas, Belize,



	Anguilla	Antigua and Barbuda	Bahamas	Barbados	Belize	Cayman Islands	Cuba	Dominica	Dominican Republic	Grenada	Guyana	Haiti	Jamaica	Montserrat	Saint Kitts and Nevis	Saint Lucia	Saint Vincent and the Grenadines	Suriname	Trinidad and Tobago
Mar-May	0	3	11	7	2	1	83	0	498	0	11	35	9	1	0	0	0	1	8
Jun-Aug	0	0	32	0	11	0	11	0	1183	0	24	166	10	0	0	0	0	66	13
Sep-Nov	0	1	120	0	131	1	40	0	649	0	114	31	237	0	0	2	0	50	97

Fig. 4. Number of Death for each of three months from March to November 2020.

Table 2
Classic linear regression models of COVID-19 in the Caribbean.

	Model 1 COVID-19 Deaths SWLS	Model 2 COVID-19 Cases SWLS	Model 3 COVID-19 Deaths WLS	Model 4 COVID-19 Cases WLS
A	48.6195*** (10.2526)	6.77395*** (0.56507)	156.337*** (46.1420)	7.0887** (1.03173)
Spatial Lag (W)	0.0407*** (0.003702)	0.0000004 (0.0000063)	–	–
COVID-19 Cases	0.0161*** (26.2179)	–	0.0158*** (0.029734)	–
Income/Capita	–	- 0.000067** (0.0000283)	–	- 0.000075* (0.0000373)
Pop. Density	–	- 0.001408 (0.001766)	–	- 0.0016939 (0.002589)
Gov. Health Expenditure	−0.00257 (0.01313)	–	0.015206 (0.029734	–
Land and Sea Bridge with Continental Mainland	–	3.85976*** (0.81210)	–	3.95497*** (0.710562)
Priv. Health Expenditure	0.02431*** (0.00546)	–	0.002635 (4.55837)	–
Hospital Beds per 1000 people	−16.8585*** (1.89223)		−20.2647*** (5.22092)	
Diabetes Prevalence in country	9.64996*** (1.40924)		3.57776 (3.08666)	
Hypertension Prevalence in country	−5.27718*** (0.548170)		−5.30269*** (1.17714)	
Direct Air bridge from COVID-19 Epicentre	–	0.843960 (0.51279)	–	0.943649 (0.767034)
Length of Air bridge closure	–	−0.281931*** (0.05593)	–	−0.281698** (0.099067)
Prob>*F*	0.000***	0.000***	0.000***	0.000***
R-value	0.999	0.980	0.999	0.859

Notes: Where SWLS represents spatial weighted least squares and WLS represents weighted least squares values within the () are the standard errors for the coefficients; *, ** and *** are statistical significance at 10%, 5% and 1% respectively; Prob>*F* and R-Sq. are explanatory measures for the models; All models were adjusted for Heteroskedasticity and the Variance Inflation Factor (VIF) was used to test for multicollinearity.

Jamaica, Cuba, Haiti, Dominican Republic, Guyana, Suriname and Trinidad and Tobago have the highest number of cases in the region and all have a land and sea bridge with the mainland. Guyana and Suriname have land borders with Brazil and Venezuela for which major movements occur mainly through smuggling activities (Liang and Moonsammy, 2020). Trinidad and Tobago shares a narrow sea passage with Venezuela which is currently a channel for the illegal movement of emigrants from Venezuela (Mohan, 2019). Belize has land borders with Guatemala and Mexico and has several land conflict issues with Guatemala and is often considered a transitionary boundary area for undocumented migrants and illegal smuggling from Central America to North America (Hanson et al., 2007; Perez et al., 2009). The Bahamas, Jamaica, Haiti, Dominican Republic and Cuba has a well-documented history of the movement of illegal migrants and illegal smuggling activities between these countries and the United States (Kahn, 2019). The empirical evidence and literature supports the position that COVID-19 in the Caribbean is currently being perpetuated by the unregulated movement of persons between the land and sea bridges in the Caribbean with the mainland Americas. To further emphasize the spread of COVID-19 attributed to the intercountry movement of people, the variable for airport closures showed an inverse relationship with the number of COVID-19 cases. Interpreting this variable shows that as the length of airport closure increases, the number of expected cases will decrease.

For the models with COVID-19 related deaths as the dependant variable, there were varying results between the spatial and non-spatial aspects. In both models, the number of COVID-19 cases, the number of hospital beds per 1000 persons and the proliferation of hypertension were all statistically significant at 1%. The models show a positive relationship between COVID-19 deaths and cases which emphasizes the linearity between these variables and corroborates with the literature outlined by Adekunle et al. (2020) and Sardokie and Owusu (2020). Overwhelmingly, the results showed an inverse relationship between the number of hospital beds per 1000 persons and the number of COVID-19 related deaths. Thus, as the number of hospital beds increases in a country, the number of COVID-19 related deaths will decrease. This findings emphasizes the importance of hospital access and facilities needed to provide the necessary medical care for COVID-19. Looking at the variables on health care expenditure, the government expenditure on health care was not seen as significant. For the spatial model only, private health expenditure had a significant and positive coefficient. The data on health expenditure cannot provide any conclusive evidence to determine if the current level of investments made on the health care sector has any influence in curbing COVID-19 deaths. More empirical research is needed with disaggregated data looking at the amount of expenditure made towards the necessary health facilities and services monthly in each country in response to the pandemic.

With respect to the prevalence of diabetes and hypertension in the countries, the spatial model showed a significant and positive relationship between the prevalence of diabetes in the country and the number of COVID-19 related deaths. This finding corroborates with the literature as diabetics have increased risks of death from contracting COVID-19. The diabetes variable was not significant in the non-spatial model. Hypertension had a negative relationship with COVID-19 deaths in both models. Though this contradicts with the literature on risk factors for COVID-19 (Jordan et al., 2020; Muniyappa and Gubbi, 2020), the findings can be attributed to the data sourced for hypertension and diabetes. National statistics were used as the variables for diabetes and hypertension and many Caribbean countries have a high prevalence of hypertension and diabetes but low numbers of COVID-19 related deaths. The results do demonstrate some statistical effects but further work is needed looking at the pre-medical conditions of persons who died from COVID-19 to better empirically establish this relationship regionally. The spatial lag variable for the spatial model was seen as significant and positively impacting COVID-19 related deaths which is another indication of the spatial impact of COVID-19 in the Caribbean.

All models adopted used a model specification that corrected for heteroskedasticity and had a statistically significant F value. The variance inflation factor (VIF) was assessed for all models. The VIF test showed all regressors had a value less than 10 which indicates no multicollinearity present. The models specified were deemed acceptable as diagnostics shows the models upheld the Gauss-Markov assumptions for linear regression and variables have a good fit as regressors. The explanatory power range between 0.85 – 0.99 showing well defined model regressors in explaining the variations observed in COVID-19 cases and deaths. Thus, the models seems to be well specified and provide good interpretive value to the discourse of COVID-19 in the Caribbean.

Conclusion

This study demonstrates that the COVID-19 pandemic has firmly established a footprint in the Caribbean region. Spatial and statistical modelling were done based on prior models and extended to include several socio-economic dimensions. The countries in the Caribbean have a fluctuating rate of spread and attributable deaths primarily dependant on spatial factors and the availability of medical facilities. Countries with the highest population such as the Dominican Republic and Cuba were affected the most which is consistent with findings from the literature worldwide on the impacts of population in viral transmission (Candido et al., 2020; Chinazzi et al., 2020; Fanelli and Piazza, 2020; Rodriguez-Morales et al., 2020). The Caribbean region essentially implemented similar social distancing policy measures with subtle variations which include restricting public gatherings and closing airports. The region's health policies complied with international standards established by the World Health Organization.

In analysing the demographic, economic and spatial factors that can influence the number of COVID-19 cases and deaths, our models indicate that population density was not a factor affecting the number of COVID-19 cases regionally. Our empirical evidence showed that the movement of persons from the mainland to the Caribbean through the land and sea bridges seems to be the most enabling factor for COVID-19 continuing to spread in the region to date. Most likely illegal migration and smuggling routes are the main contributors to this movement which presents a policy challenge for countries to secure their land and sea borders. In terms of factors influencing the number of deaths, the most notable finding was the inverse relationship between the number of hospital beds and reduction in attributable deaths. Whereby investments in the health sector was inconclusive as a variable, the Caribbean followed the standard health guidelines and many of the smaller Caribbean islands have managed to stabilize cases and deaths reflecting the effectiveness of the management and policies adopted by their public health system. The Caribbean countries explored for this study have contrasting challenges in their public health system and more work is needed on the individual country's capacity to manage and deal with increasing cases. The COVID-19 management paradigm for the public health care systems in countries such as Barbados and St. Kitts who have relatively small numbers in cases and deaths and have stabilized presently is quite different to that of the Dominican Republic and Cuba where cases and deaths are still rapidly increasing.

The lessons of COVID-19 in the Caribbean is still at its infancy and as such, more in-depth research is needed. The effects of this pandemic have many levels to explore within the Caribbean. Going beyond this study, further research is needed on extended models to include other social and economic impacts such as the decline in tourism, disaggregated observations on health expenditure and a retroactive look at the pre-medical conditions of COVID-19 victims to provide more empirical evidence of the risks associated with diabetes, hypertension and other non-communicable diseases for the region. COVID-19 is a unique and burdening challenge for the Caribbean. The findings of this study can have significant implications for the policy and strategic management agenda for future outbreaks of a similar nature. The Caribbean can learn from their experiences in order to better prepare for future pandemic spreads by anticipating its connectivity to disease epicentres, looking at border security as the pandemic has now revealed an additional threat from the illegal movement of people and investing in hospital spaces, facilities and services as this can potential reduce mortality rates. This paper was a modest contribution in understanding the spread of COVID-19 in the Caribbean. As the United Nations Secretary General, Antonio Guterres, while commenting on the pandemic said: *"With common cause for common sense and facts, we can defeat COVID-19 – and build a healthier, more equitable, just and resilient world"*. We sincerely hope that preliminary observations and analyses presented in this paper would contribute to that cause and ensure that COVID-19 pandemic is eliminated in the Caribbean.

Author statement

Stephan Moonsammy: Conceptualization, Methodology, Data analysis, Writing- Original draft preparation. **Temitope Oyedotun**: Data curation, Data analysis Writing- Original draft preparation. **Donna-Marie Renn-Moonsammy**: Writing- Reviewing and Editing. **Temitayo Oyedotun**: Writing- Reviewing and Editing.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

None.

References

Adekunle, I.A., Onanuga, T.A., Akinola, O.O., Ogunbanjo, O.W., 2020. "Modelling spatial variations of coronavirus disease (COVID-19) in Africa.". Sci. Total Environ. 729 (2020), 138998. doi:10.1016/j.scitotenv.2020.138998, https://doi.org/.

Badr, H.S., Du, H., Marshall, M., Dong, E., Squire, M.M., Gardner, L.M., 2020. "Association between mobility patterns and COVID-19 transmission in the USA: a mathematical modelling study.". Infect. Dis. 20 (11), 1247–1254. doi:10.1016/S1473-3099(20)30553-3, https://doi.org/.

Bhadra, A., Mukherjee, A., Sarkar, K., 2020. "Impact of population density on COVID-19 infected and mortality rate in India.". Model. Earth Syst. Environ. (2020) doi:10.1007/s40808-020-00984-7, https://doi.org/.

Burki, T., 2020. COVID-19 in Latin America. Newsdesk Vol. 20 (ISSUE 5), P547–P548. doi:10.1016/S1473-3099(20)30303-0, MAY 01, 2020https://doi.org/.

Candido, D.D.S., Wattsm, A., Abade, L., Kraemer, M.U.G., Pybus, O.G., Croda, J., de Oliveira, W., Khna, K., Sabino, E.C., Faria, N.R., 2020. Routes for COVID-19 importation in Brazil. J. Travel Med. 27 (3). doi:10.1093/jtm/taaa042.

Chinazzi, M., Davis, J.T., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., Piontti, A.P., Mu, K., Rossi, L., Sun, K., Viboud, C., Xiong, X., Yu, H., Halloran, M.E., Longini, I.M., Vespignani, A., 2020. The effects of travel restrictions on the spread of the 2019 novel corona virus (COVID-19) outbreak. Science 368 (6489), 395–400.

Fanelli, D., Piazza, F., 2020. "Analysis and forecast of COVID-19 spreading in China, Italy and France.". Chaos Solit. Fract. 134, 1–12. doi:10.1016/j.chaos.2020.109761, https://doi.org/.

Giordano, G., Blanchini, F., Bruno, R., Colaneri, P., Di Filippo, A., Di Matteo, A., Colaneri, M., 2020. Modelling the COVID-19 epidemic and implementation of population-wide interventions in Italy. Nat. Med. 26, 855–860.

Guan, W., Ni, Z., Hu, Y., Liang, W., Ou, C., He, J., Liu, L., Shan, H., Lei, C., Hui, D.S.C., Du, B., Li, L., Zeng, G., Yuen, K.-Y., Chen, R., Tang, C., Wang, T., Chen, P., Xiang, J., Li, S., Wang, J.-.L., Liang, Z., Peng, Y., Wei, L., Liu, Y., Y.Hu, P.Peng, Wang, J., J, Liu, Chen, Z., Li, G., Zheng, Z., Qiu, S., Luo, J., Ye, C., Zhu, S., Zhong, N., 2020. Clinical characteristics of corona virus disease 2019 in China. N. Engl. J. Med. 382 (18), 1708–1720.

Guilani, D., M.M. Dickson, G. Espa, and F. Santi. 2020. "Modeling and predicting the spatio-temporal spread of Corona virus disease 2019(COVID-19) in Italy."*Lancet North Am. Ed.*. THELANCET-d-20-04320.

Hanson, R., Warchol, G., Zupan, L., 2007. "Policing Paradise: law and Disorder in Brazil.". Police. Pract. Res. 5 (3), 241–257.

Hartmann-Boyce, J., Morris, E., Goyder, C., Kinton, J., Perring, J., Nunan, D., Mahtani, K., Buse, J.B., Prato, S.D., Ji, L., Roussel, R., Khunti, K., 2020. "Diabetes and COVID-19: risks, management, and learnings from other national disasters.". Diabetes Care. 43, 1695–1703.

Jordan, R.E., Adab, P., Cheng, K.K., 2020. "COVID-19: risk factors for severe disease and death.". BMJ (2020) doi:10.1136/bmj.m1198.

Kadi, N., Khelfaoui, M., 2020. "Population density, a factor in the spread of COVID-19 in Algeria: statistic study.". Bull. Natl Res. Centre 44, 1–7. doi:10.1186/s42269-020-00393-x, https://doi.org/.

Kahn, J., 2019. "Smugglers, migrants and demons: cosmographies of mobility in the northern Caribbean. Am. Ethnol. 46 (4), 470–481. doi:10.1111/amet.12831, https://doi.org/.

Kang, D., Choi, H., Kim, J.-.H., Choi, J., 2020. "Spatial epidemic dynamics of the COVID-19 outbreak in China.". Int. J. Infect. Dis. 94, 96–102.

Liang, T., Moonsammy, S., 2020. "Evaluating the impact of small-scale mining on the achievement of the sustainable development goals in Guyana.". Environ. Sci. Policy 116, 147–159.

Liu, Y., Gayle, A.A., Wilder-Smith, A., Rocklö, J., 2020. The reproductive number of COVID-19 is higher compared to SARS corona virus. J. Med. Virol. 27 (2). doi:10.1093/jtm/taaa021.

Matas, M., A. Picornell, C. Cifuentes, A. Payeras, A. Bassa, F. Homar, F. Gonzalez-Candelas, F.X. Lopez-Labrador, A. Moya, M.M. Ramon, and J.A. Castro. 2013 "Generalized Linear Models (GLM) framework for the association of host variables and viral strains with liver fibrosis in HCV/HIV co-infected patients."*Infect. Genet. Evol.*13: 284–291.

Mohan, S.S., 2019. "A 'migrant registration framework': counting Venezuelan immigrants in Trinidad and Tobago.". Oxford Monit. Forced Migrat. 8 (1), 41–45.

Muniyappa, R., Gubbi, S., 2020. "COVID-19 pandemic, coronaviruses, and diabetes mellitus.". Am. J Physiol. Endocrinol. Metab. 318, 736–741.

Murphy, M.M., S.M. Jeyaseelan, C. Howitt, N. Greaves, H. Harewood, K.R. Quimby, N. Sobers, R.C. Landis, K.D. Rocke, and I.R. Hambleton. 2020 "COVID-19 containment in the Caribbean: the experience of small island developing states."*Res. Glob.*2: 1–10.

Nguimkeu, P., Tadadjeu, S., 2021. "Why is the Number of COVID-19 cases lower than expected in Sub-Saharan Africa? A cross-sectional analysis of the role of demographic and geographic factors. World Dev. 138, 1–10.

Ogundokun, R.O., Lukman, A.F., Kibria, G.B.M., Awotunde, J.B., Aladeitan, B.B., 2020. "Predicting modelling of COVID-19 confirmed cases in Nigeria.". Infect. Dis. Model. 5, 543–548.

Oyedotun, T.D.T., Moonsammy, S., 2020. Spatiotemporal variation of COVID-19 and its spread in South America: a rapid assessment. Ann. Am. Assoc. Geogr. doi:10.1080/24694452.2020.1830024, https://doi.org/.

Perez, A., Chin-Ta, C., Afero, F., 2009. "Belize-Guatemala territorial dispute and its implications for conservation.". Trop. Conserv. Sci. 2 (1), 11–24.

Rath, S., Tripathy, A., Tripathy, A.R., 2020. "Prediction of new active cases of corona virus disease (COVID-19) pandemic using multiple linear regression model.". Diabetes Metab. Syndr.: Clin. Res. Rev. 14, 1467–1474.

Rocklöv, J., Sjödin, H., 2020. High population densities catalyse the spread of COVID-19. J. Travel Med. 27 (3), 1–2.

Rodriguez-Morales, A.J., Gallego, V., Méndez, C.A., Zambrano, L.I., Franco-Paredes, C., Suárez, J.A., Rodriguez-Enciso, H.D., Balbin-Ramon, G.J., Savio-Larriera, E., Risquez, A., Cimerman, S., 2020. "COVID-19 in Latin America: the implications of the first confirmed case in Brazil.". Travel Med. Infect. Dis. doi:10.1016/j.tmaid.2020.101613, https://doi.org/.

Rothe, C., Schunk, M., Sothmann, P., Bretzel, G., Froeschl, G., Wallrauch, C., Zimmer, T., V.Thiel, C.Janke, Guggemos, W., Seilmaier, M., Drosten, C., Vollmar, P., Zwirglmaier, K., Zange, S., Wölfel, R., Hoelscher, M., 2020. Transmission of 2019-nCoV infection from an asymptomatic contact in Germany. N. Engl. J. Med. 382 (1), 970–971.

Saqlain, M., Munir, M.M., Rehman, S.U., Gulzar, A., Naz, S., Ahmed, Z., Tahir, A.H., Mashhood, M., 2020. Knowledge, attitude, practice and perceived barriers among healthcare workers regarding COVID-19: a cross sectional survey from Pakistan. J. Hosp. Infect. 105, 419–423.

Sarkodie, S.A., Owusu, P.A., 2020. Investigating the cases of novel corona virus disease (COVID-19) in China using dynamic statistical techniques. Heliyon 6 1–5.

Szmaragd, C., Nichols, R.A., Balloux, F., 2006. "A novel approach to characterize pathogen candidate genetic polymorphisms involved in clinical outcome.". Infect. Genet. Evolu. 6, 38–45.

Tobler, W., 2020. "A computer movie simulating urban growth in the Detroit region.". Econ. Geogr. 46, 234–240.

World Health Organization. 2020. "Novel Coronavirus (2019-ncov) - situation report –22, 2020." Accessed 3rd March 2020. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200211-sitrep-22-ncov.pdf?sfvrsn¼fb6d49b1_2.

Zhang, S., Y. Wang, A.A. Jahanshahi, J. Jia, V.G.H. Schmitt.. 2020. "First study on mental distress in Brazil during the COVID-19 crisis." medRxiv, doi: https://doi.org/10.1101/2020.04.18.20070896.