The spread of COVID-19 at Hot-Temperature Places With Different Curfew Situations Using Copula Models

Fadhah Alanazi
Deanship of Educational Services,
Department of General Sciences,
Prince Sultan University,
Riyadh, Saudi Arabia
Email:fanazi@psu.edu.sa

ABSTRACT

The infectious coronavirus disease 2019 (COVID-19) has become a serious global pandemic. Different studies have shown that increasing temperature can play a crucial role in the spread of the virus. Most of these studies were limited to winter or moderate temperature levels and were conducted using conventional models. However, traditional models are too simplistic to investigate complex, non-linear relationships and suffer from some restrictions. Therefore, we employed copula models to examine the impact of high temperatures on virus transmission. The findings from the copula models showed that there was a weak to moderate effect of temperature on the number of infections and the effect almost vanished under a lockdown policy. Therefore, this study provides new insight into the relationship between COVID-19 and temperature, both with and without social isolation practices. Such results can lead to improvements in our understanding of this new virus. In particular, the results derived from the copula models examined here, unlike existing traditional models, provide evidence that there is no substantial influence of high temperatures on the active COVID-19 outbreak situation. In addition, the results indicate that the transmission of COVID-19 is strongly influenced by social isolation practices.

INTRODUCTION

In December 2019, a novel infectious disease termed coronavirus disease 2019 (COVID-19) was discovered in Wuhan city, Hubei province, China. Subsequently, and through human-to-human transmission, this virus has caused a global pandemic. COVID-19 is characterized by clinical features similar to those caused by severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle Eastern respiratory syndrome coronavirus (MERS-CoV) infections, such as a fever and dry cough [1]. Previous studies have shown that meteorological variables can affect the transmission and survival of coronaviruses [2], [3]. Earlier research [3] found that MERS-CoV is most active at high temperatures and low humidity.

Notably, recent studies have shown that warm weather and high humidity may be important factors for reducing the spread of COVID-19 (e.g., see [4]). Conversely, some existing studies have found that increasing temperatures will not affect the transmission of COVID-19 (e.g., see [5], [6]). However, most of these studies were limited to winter or low-temperature weather with a small number of observations. Hence, there is still no definitive evidence as to whether there is a negative association between environmental variables and the spread of COVID-19 in extremely hot or cold locations [4]. Besides, most previous studies were performed using traditional models, which are too simplistic and may be unable to deal with complex, non-linear dependency patterns. Thus, further research to understand the activity of COVID-19 under high-temperature conditions is warranted. One important benefit of using a copula model is that one can model the marginal distribution independently from the dependency structures, which are completely captured via the copula function. Another benefit of using a copula model is that the margins do not need to follow the same parametric family. Furthermore, many copula families exist, each with its own capability to describe the unique dependency structure. Hence, various types of associations can be discovered via copula models. In addition, such an association should be investigated not only in regard to weather variables, but also by taking into account the lockdown situation at these locations. Hence, this study aimed to perform flexible statistical modeling with a copula model to improve our knowledge about the spread of the virus in hot locations with different curfew levels. Specifically, we investigated the impact of high temperatures on the number of confirmed cases in the cities of Riyadh, Jeddah, and Mecca in Saudi Arabia, and these cities were selected for several reasons. First, Saudi Arabia has been strongly affected by MERS-CoV [7], [8], which produces a similar severe respiratory illness as COVID-19. Second, the highest numbers of confirmed cases in Saudi Arabia have been recorded in Riyadh, Jeddah, and
Mecca, which are three of the hottest areas in Saudi Arabia. Third, because of the transmission of COVID-19, Mecca and Jeddah have been placed under a series of lockdowns for a long time. Riyadh, however, was only placed under a curfew for a short period. Hence, these cities represent strong to moderate lockdown situations, which could be a factor critical to understanding the effects of high temperatures on the spread of COVID-19. By using the data from these cities and capitalizing on the flexibility of copula models, we aimed to provide clear evidence on the association between high temperatures and confirmed cases of COVID-19.

MATERIALS AND METHODS

Data collection

For this study, daily counts of confirmed cases for the study period were collected from official reports [9] based on information [10] for Saudi Arabia. The daily average temperature data for the same period were obtained from the Weather Underground Company [11].

Data analysis

Both the COVID-19 confirmed cases and the average temperature data demonstrated a non-normal distribution for all cities.

Copula

Copulas are multivariate cumulative distribution functions with uniform marginal distributions on (0,1) such that:

\[ C : [0,1]^n \rightarrow [0,1], \quad n \geq 2. \tag{1} \]

Sklar’s theorem [12] is the key rule of the copula function, and it can be introduced as follows:

**Theorem 0.1 (Sklar’s theorem):** If \( F \) is an \( n \)-variate distribution function with univariate margins \( F_1, F_2, \ldots, F_n \), then there exists an \( n \)-variate copula function, \( C \), such that \( \forall \) \( x = (x_1, \ldots, x_n) \in R^n \):

\[ F(x_1, x_2, \ldots, x_n) = C(F_1(x_1), F_2(x_2), \ldots, F_n(x_n)). \tag{2} \]

If the margins are continuous, then the copula

\[ C(u_1, u_2, \ldots, u_n) = F(F_1^{-1}(u_1), F_2^{-1}(u_2), \ldots, F_n^{-1}(u_n)) \tag{3} \]

is unique, where \( F^{-1} \) is the inverse function of the margins and \( u \in [0,1]^n \). Conversely, if \( F_1, \ldots, F_n \) are the marginal distribution functions and \( C \) is a copula function, then the function \( F \) (defined by equation (2)) is a joint distribution function with margins \( F_1, \ldots, F_n \).

In this study, we consider an arbitrary number of copula types including the Joe, Frank, and Clayton copulas, as well as their rotation types.

- **Frank copula** is a one-parametric symmetric Archimedean copula. The Frank copula can control both the negative and positive dependency pattern, where

The strongest dependency occurs at the center of the distribution. Its density function is:

\[ c(u_1, u_2) = \theta(e^{-\theta} - 1) \frac{e^{-\theta(u_1 + u_2)}}{e^{-\theta} - 1 + (e^{-\theta u_1} - 1)(e^{-\theta u_2} - 1)}. \tag{4} \]

- **Clayton copula** is a one-parametric \((\theta > 0)\) non-symmetric Archimedean copula. It is a lower positive tail dependence copula, and its density function is:

\[ c(u_1, u_2) = (1 + \theta)(u_1^\theta + u_2^\theta - 1)\frac{1}{\theta^2}. \tag{5} \]

- **Joe copula**, in contrast to the Clayton copula, is a one-parametric upper tail Archimedean copula, and its density function is:

\[ c(u_1, u_2) = \frac{(1 - u_1)^\theta + (u_2)^\theta - 1}{(1 - u_1)^\theta(1 - u_2)^\theta - \theta - 1}. \tag{6} \]

In this study, we applied the so-called pseudo maximum-likelihood method (PML) to estimate the parameters for the selected copula function. **PML** is introduced by [13] as a two-step estimation method. With this method, the margins are estimated non-parametrically via their empirical cumulative distribution function at first, and then, the copula parameter \((\theta_c)\) is estimated at the second step. By using PML, the copula parameter is estimated by maximizing the copula density, i.e.,

\[ L_{\text{PML}}(\theta_c) = \sum_{i=1}^{n} \log[c(u_{1i}, u_{2i}; \theta_c)], \tag{7} \]

where \( u_1 = \hat{F}_1(x_1; \alpha_1) \) and \( u_2 = \hat{F}_2(x_2; \alpha_2) \) are the empirical probability integral transform of variable \( X_1 \) and \( X_2 \), respectively.

A. Goodness-of-fit test

As there is a wide range of copula functions, it is necessary to test the copula shape with the best fit. Therefore, we will use the Akaike Information Criterion (AIC) of [14] and the Bayesian Information Criterion (BIC) of [15] to select the right copula. **AIC** and **BIC** can be given by:

\[ \text{AIC} = -2 \ln L(\hat{\theta}) + 2P, \tag{8} \]

\[ \text{BIC} = -2 \ln L(\hat{\theta}) + P \ln (N), \tag{9} \]

where \( \hat{\theta} \) is the estimated value of the parameters, and \( P \) is the number of the model parameters.

RESULTS AND DISCUSSION

Descriptive results

Table I shows the summary statistics for the daily data on temperature and COVID-19 confirmed cases in the cities of Riyadh, Mecca, and Jeddah.
Discussion of the Copula model

In accordance with Table (II), Frank copulas with a moderate positive dependency ($\theta = 8.52$, $\tau = 0.62$) and ($\theta = 7.47$, $\tau = 0.57$) were selected for Riyadh and Jeddah, respectively. The results indicate that there is a positive relationship between temperature and the spread of COVID-19 in moderate and high temperatures. However, these two variables became independent at extreme values. Therefore, the results provide clear evidence that COVID-19 can still remain an active virus in hot places. In the case of Mecca, the survival Joe copula with a low dependency level ($\theta = 1.92$, $\tau = 0.34$) was selected as the most appropriate copula function with these data, as there was only a very weak dependency pattern between high temperatures and confirmed cases at the low values. This relationship reflects the period before the series of lockdowns in the city of Mecca. During the curfew, there was no relationship detected between the spread of COVID-19 and the temperature. Therefore, there was another important factor driving the active situation of this new virus, namely, the lockdown situation. During the study period, Mecca experienced a long lockdown period, while duration of curfew in Riyadh was the shortest. These factors may explain the similarity in copula results for Riyadh and Jeddah and the low dependency pattern in the case of Mecca. In consideration of these last findings, we can conclude that high temperatures had only a weak to moderate effect on the transmission of COVID-19 if there was a partial curfew policy in place. However, this effect vanished under the condition of strong social isolation. Hence, even in hot places, COVID-19 can still spread readily when no social distancing is implemented.

CONCLUSION

This study examined the effect of high temperatures on the spread of COVID-19 in hot climates under different curfew situations using copula models. We applied the models to the cities of Riyadh, Jeddah, and Mecca in Saudi Arabia. For Riyadh and Jeddah, which had almost the same average temperature level, the association between temperature and confirmed cases of COVID-19 reflected a moderate positive Frank copula. However, the number of COVID-19 cases in Riyadh was higher than the number in Jeddah. Hence, the transmission of this virus in these two cities may have been affected by the curfew level and not by the high temperature. In the case of Mecca, which had a temperature level (slightly) less than that of Riyadh and Jeddah, there was a very weak dependency between temperature and the number of COVID-19 cases. However, the number of confirmed cases of COVID-19 in Mecca was very close to the number in Jeddah. In addition, Mecca was under a strong 24 hour lockdown for more than half of the observed data set. Therefore, there is clear evidence that high temperatures are not able to stop the spread of this virus if there is no social isolation. Clearly, lockdowns represent the most effective strategy to prevent the spread of this virus.

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