



Impact of weather on COVID-19 transmission in south Asian countries: An application of the ARIMAX model

Md. Sabbir Hossain, Sulaiman Ahmed, Md. Jamal Uddin*

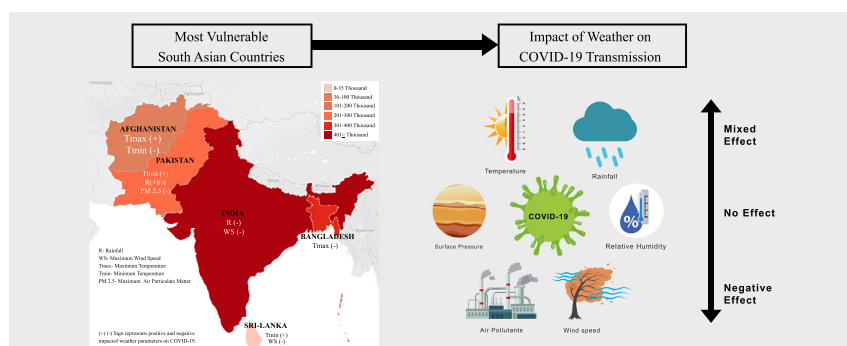
Department of Statistics, Shahjalal University of Science & Technology, Sylhet 3114, Bangladesh



HIGHLIGHTS

- A new study examined the impact of weather on COVID-19 transmission for the first time in five south Asian countries.
- Autoregressive Integrated Moving Average with Explanatory Variables (ARIMAX) model was used to assess the impact.
- Lower wind speed could modulate the transmission of COVID-19.
- Excess rainfall could reduce the transmission whereas the temperature impact was not consistent throughout the countries.
- Low concentrations of air pollutants can increase the risk of infection, but it also depends on rainfall.

GRAPHICAL ABSTRACT



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ABSTRACT

We aimed to examine the impact of weather on COVID-19 confirmed cases in South Asian countries, namely, Afghanistan, Bangladesh, India, Pakistan, and Sri Lanka. Data on daily confirmed cases, together with weather parameters, were collected from the first day of COVID confirmed cases in each country to 31 August 2020. The weather parameters were Rainfall (mm), relative humidity (%), maximum and minimum temperature ($^{\circ}\text{C}$), surface pressure (kPa), maximum air pollutants matter PM 2.5 ($\mu\text{g}/\text{m}^3$) and maximum wind speed (m/s). Data were analyzed for each investigated countries separately by using the Autoregressive Integrated Moving Average with Explanatory Variables (ARIMAX) model. We found that maximum wind speed had significant negative impact on COVID-19 transmission in India (-209.45 , 95% confidence interval (CI): -369.13 , -49.77) and Sri Lanka (-2.77 , 95% CI: -4.77 , -0.77). Apart from India, temperature had mixed effects (i.e., positive or negative) in four countries in South Asia. For example, maximum temperature had negative impact (-30.52 , 95% CI: -60.24 , -0.78) in Bangladesh and positive impact (5.10 , 95% CI: 0.06 , 10.14) in Afghanistan. Whereas rainfall had negative effects (-48.64 , 95% CI: -80.17 , -17.09) in India and mixed effects in Pakistan. Besides, maximum air pollutants matter PM 2.5 was negatively associated with the confirmed cases of COVID-19. In conclusion, maximum wind speed, rainfall, air pollutants (maximum PM 2.5) and temperature are four variables that could play a vital role in the transmission of COVID-19. Although there is a mixed conclusion regarding weather parameters and COVID-19 transmission, we recommend developing environmental policies regarding the transmission of COVID-19 in South Asian countries.

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* Corresponding author.

E-mail addresses: sabbir05@student.sust.edu (M.S. Hossain), sulaimanahmed013@gmail.com (S. Ahmed), jamal-sta@sust.edu (M.J. Uddin).

1. Introduction

Novel coronavirus (COVID-19) is a respiratory disease caused by severe acute coronavirus syndrome 2 (SARS-CoV-2) (F. Wu et al., 2020). Due to its highly human-to-human transmission nature (Bogoch et al., 2020; C. Wang et al., 2020) the disease spread rapidly throughout the world and was declared a global pandemic by world health organization (WHO) on 11 March 2020. Over 25 million confirmed cases (25,094,338) and 844,060 COVID-19 deaths were reported around the world until 31 August 2020 (World Health Organization, 2020).

Several studies suggested that weather parameters like temperature, rainfall, humidity, wind speed, and air pollutants may influence the transmission of the COVID-19 (Ahmadi et al., 2020; Al-Rousan and Al-Najjar, 2020; Bashir et al., 2020; Jüni et al., 2020; Liu et al., 2020; Qi et al., 2020; Sobral et al., 2020; Tosepu et al., 2020; Y. Wu et al., 2020; Zoran et al., 2020). For example, Liu et al. (2020), Qi et al. (2020), Sobral et al. (2020) and Y. Wu et al. (2020) demonstrated that the transmission of COVID-19 infection is suppressed as temperature increases in China and some other regions around the world. Moreover, Al-Rousan and Al-Najjar (2020), Tosepu et al. (2020) and Zoran et al. (2020) reported a significant positive correlation in China, Indonesia and Italy while in Iran, Ahmadi et al. (2020) and in 144 geopolitical areas worldwide, Jüni et al. (2020) reported no significant correlation between temperature and COVID-19 transmission. Furthermore, Liu et al. (2020), Qi et al. (2020) and Y. Wu et al. (2020) stated humidity as one of the important weather parameters that significantly reduce the virus transmission of COVID-19. But some studies reported no significant impact of humidity on the COVID-19 epidemic (Bashir et al., 2020; Tosepu et al., 2020). Also, Ahmadi et al. (2020), Sobral et al. (2020) and Zoran et al. (2020) investigated the impact of rainfall, air pollutants, and wind speed on COVID-19 and found that rainfall and air pollutants had a positive impact while wind speed had a significant negative impact on COVID-19. However, Poirier et al. (2020) reported that weather parameters alone could not decline the coronavirus transmission.

Several statistical methods such as correlation, regression analysis, generalized additive model (Ma et al., 2020; Qi et al., 2020; Y. Wu et al., 2020; Xie and Zhu, 2020), and generalized linear model (Liu et al., 2020), are extensively applied to assess the impact of environmental factors on COVID-19 transmissibility. However, among those methods, most of the studies used correlation and regression analysis techniques (Guo et al., 2020; Jüni et al., 2020; Li et al., 2020; Şahin, 2020; Sobral et al., 2020; Tosepu et al., 2020; Zoran et al., 2020). These studies have used the regression model for time series data but have not determined the stationary condition of the data, although stationary is the precondition for implementing any regression analysis techniques with time-series data (Chen et al., 2004). As a result, these studies could have produced incorrect estimates due to misspecification of the applied models. A well-defined time series technique, such as the Autoregressive Integrated Moving Average with Explanatory Variables (ARIMAX) model, is therefore essential to apply in order to eliminate the long-term trend of COVID-19 epidemic and to consider environmental factors as external regressors too. In addition, due to lack of data availability, most of the study was conducted at the birthplace of COVID-19, Wuhan, China and a small number of studies in other regions of the world, particularly in South Asian countries where the risk of COVID-19 transmission rate is very high due to low-income people and high population density. Thus, in this study, we aimed to examine the impact of weather (climate variables and air pollutants) on COVID-19 transmission by using the ARIMAX model in South Asian countries such as Bangladesh, India, Pakistan, Afghanistan and Sri Lanka.

2. Methods

2.1. Data sources and properties

This study was accumulated different types of data, including daily COVID-19, climate, and air pollutants datasets from the first unequal date of COVID-19 confirmed cases to 31 August 2020 of five South Asian countries, such as Afghanistan, Bangladesh, India, Pakistan, and Sri Lanka. The daily COVID-19 confirmed cases were gathered from the Humanitarian Data Exchange website (Humanitarian Data Exchange, 2020). We also included different types of climate data parameters based on a daily scale such as Rainfall (mm), Relative humidity (%), Temperatures (°C), and Surface pressure (kPa) from NASA Prediction of Worldwide Energy Resources website (NASA, 2020). Finally, we included some air parameters, maximum atmospheric particulate matter with aerodynamic diameter ≤ 2.5 (Maximum PM 2.5 $\mu\text{g}/\text{m}^3$), and maximum velocity of wind (m/s) at 10 m height (Maximum Wind Speed) were collected from Air Quality Open Data Platform website (World Air Quality Index project, 2020). We have strictly maintained the quality of our collected datasets and double-checked by two different authors. In addition, we have carefully managed our data management, checked for inconsistencies in our data, and stored all the R-codes needed to reproduce the results. More details are found in supplementary materials (S2).

Afghanistan has a dry continental climate with hot summers and cold winters where summer temperature can rise to 50 °C, but winter temperatures may dip to -25 °C (Swedish Committee for Afghanistan, 2020). Bangladesh has a subtropical monsoon climate with yearly average temperature ranges between near 26 °C to 36 °C (Discovery Bangladesh, 2020). India hosts two climatic subtypes- tropical monsoon climate and tropical wet and dry climate (Wikipedia, 2020a). The average temperature of Islamabad the capital city of Pakistan varies from 2 °C to 38 °C and annual rainfall averaging about 255 mm (Wikipedia, 2020b). Sri Lanka's climate is tropical and consists of distinct wet and dry seasons (World Travel Guide, 2020). The geographical location of five south Asian countries with cumulative COVID-19 confirmed cases up to 31 August was presented in Fig. 1.

2.2. Autoregressive integrated moving average with explanatory variables (ARIMAX) model

We used the ARIMAX model to evaluate the relationship between daily COVID-19 confirmed cases and daily climatic variables. The steps of the whole process are listed as below (Yan et al., 2017):

First, the ARIMA model was developed to the time series of confirmed cases from 1st day of confirmed cases to 31 August 2020 for each country. We used the Bayesian Information Criteria (BIC) to identify the best model for each country. The detailed procedure of the ARIMA model was found in supplementary materials (S1).

Second, cross-correlation function (CCF) was used to explore the relationship between climatic variables and COVID-19 confirmed cases for each country separately. The dependent (COVID-19 confirmed cases) and independent variables (climate variables) were pre-whitened by the previously fitted ARIMA models. Pre-whitening is an important technique for seeing which lag of the independent variable affects the dependent variable. Pre-whitening, the method of eliminating or reducing short-term stochastic persistence widely applied to the study of a variety of geophysical variables in time series (Razavi and Vogel, 2018).

Finally, climate variables selected through step 2 were incorporated as covariates into the ARIMAX model.

The maximum likelihood method was applied for the estimation of the parameters. To assess if the residual series was white noise, the Ljung-Box Q test was performed. We used R software version 3.6.1 to analyze the data (Team, 2013). To perform this analysis, MASS, Hmisc, pastecs, forecast, tseries, & lmttest packages were used.

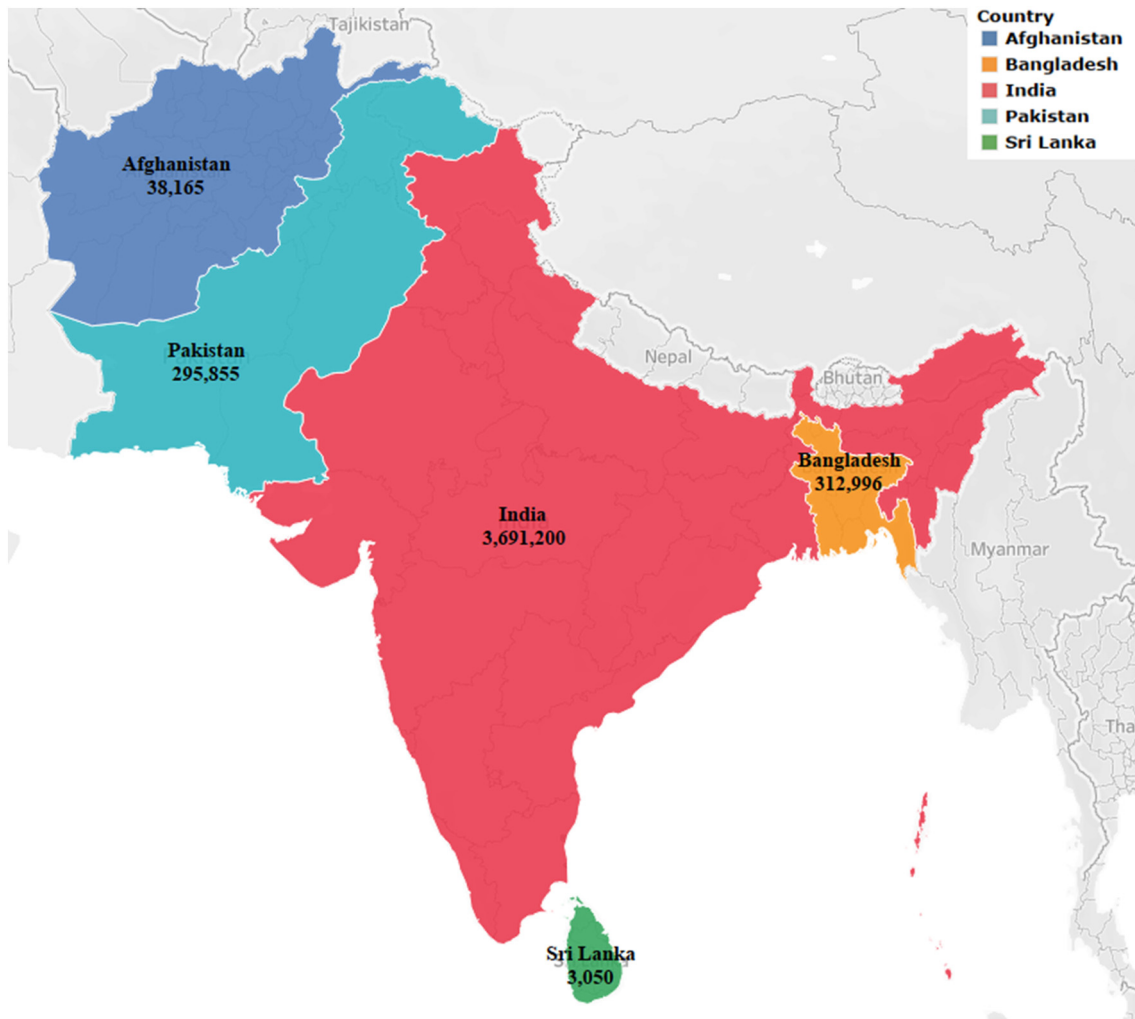


Fig. 1. South Asian countries representing the total confirmed cases until 31 August 2020.

3. Results

3.1. Descriptive analysis

Fig. 1 shows that until 31 August 2020 the highest and lowest number of confirmed COVID-19 cases were recorded in India (3,691,200), and Sri Lanka (3050), respectively. Also, Fig. 2 shows that the trend line of COVID-19 confirmed cases between Afghanistan, Bangladesh, and Pakistan is very similar, after 100 days of transmission these countries shows a decreasing trend. India have the highest rate of transmission compared to others and the transmission rate is continuously increasing from the beginning which makes India as a new hotspot of COVID-19 but the line of the pattern for Pakistan and Sri Lanka shows considerable inconsistency.

Table 1 shows descriptive statistics, e.g. minimum, maximum, median, and standard deviation of the study variables. India has the largest number of confirmed cases in one day (85687) and Sri Lanka has the lowest number of confirmed cases (300). Likewise, on average, India has the largest number of confirmed cases, and Sri Lanka has the lowest. The highest amount of rainfall (153.08 mm) was seen in India, and the second-highest in Pakistan (92.56 mm). But, Bangladesh has had more rainfall on average than in other countries. Afghanistan has the lowest humidity level (10.73%), but the highest humidity level (94.80%) has been seen in Bangladesh. The minimum temperature varies from -9.43 °C to 30.90 °C and maximum temperature from 3.38 °C to

45.40 °C in which the highest average minimum temperature was observed in Bangladesh (25.20 °C) and the highest average maximum temperature was observed in India (34.04 °C). The data showed that India has the highest average concentration of maximum PM_{2.5} (200.5 $\mu\text{g}/\text{m}^3$) and Afghanistan has the highest average maximum wind speed (6.38 m/s) than any other country.

3.2. ARIMA model for COVID-19 confirmed cases of each country

Table 2 shows the different ARIMA models across the countries. We found the ARIMA (2,1,2) was the best model for Afghanistan as opposed to other models, showing the lowest BIC value (2211.3), and similarly, ARIMA (0,1,3) for Pakistan, ARIMA (2,1,1) for Sri Lanka, ARIMA (2,2,3) for India and ARIMA (3,1,2) for Bangladesh. For each country, all the estimated parameters were statistically significant and did not show any autocorrelation (Ljung-Box test P -value is higher than 0.05) in the residual analysis except India which indicates a good fit for the selected ARIMA models (Table A.1). We didn't find any seasonal pattern of COVID confirmed cases as during this time frame most of the countries of South Asia have experienced two or three different weather seasons which might have influenced the findings of our study but the fitted ARIMA models successfully captured the variations of COVID confirmed cases in different countries excluding some significant spikes in Pakistan (Fig. A.3).

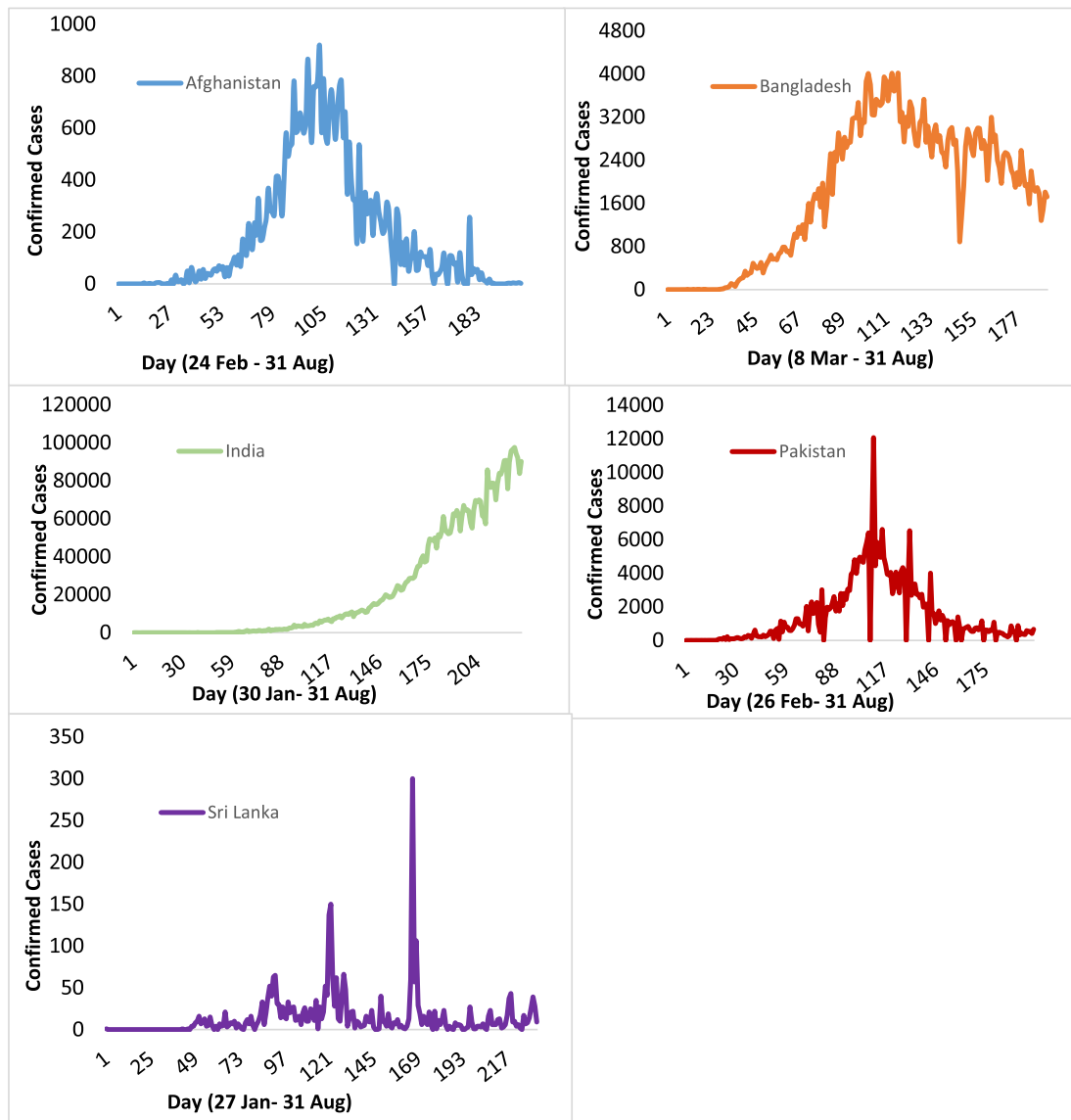


Fig. 2. Trend of COVID-19 confirmed cases of five South Asian countries starts from different dates of first confirmed cases to 31 August 2020. Here the date of first confirmed case is termed as Day 1 for each country. For example, 24th February for Afghanistan, 8th March for Bangladesh, 30th January for India, 26th February for Pakistan and 27th January for Sri Lanka.

3.3. Selection of climate variables using cross-correlation function (CCF)

Fig. 3 shows that the cross-correlation between the pre-whitened weather variables and COVID-19 confirmed cases at lags 0 to 12 days. Here only positive lags would be considered because the positive value indicated that climatic factors could affect COVID-19 confirmed cases a certain period later. For Afghanistan, except minimum temperature at lag 5 and maximum temperature at lag 12 days, all other climatic variables failed to prove the statistically significant correlation with COVID-19 confirmed cases at different lags (Fig. 3). Maximum temperature at lag 3 (Fig. 3), rainfall and maximum wind speed at lag 6 (Fig. A.1) for Bangladesh and for India rainfall at lag 6, wind speed at lag 8 (Fig. 3) and maximum particulate matter PM 2.5 at lag 2 (Fig. A.1) had a significant correlation with confirmed cases. Similarly, for Sri Lanka, and Pakistan various weather parameters at different lags have found a significant correlation with COVID-19 confirmed cases (Figs. 3, A.1).

3.4. Impact of climate parameters on COVID-19 (ARIMAX model)

At different lags, attempts were made to integrate the above-mentioned climate variables as covariates into the ARIMAX model. For

example, for Afghanistan, the ARIMAX model was set up separately by considering each of the covariates; maximum temperature at lag 12, and minimum temperature at lag 5. Likewise, the previously selected variables at different lags were considered to be covariates in the ARIMAX model for certain countries and only those were provided in Table 3, which shows a significant major effect on COVID-19.

Table 3 shows that maximum wind speed with 2 days ago ($\beta = -2.77$, 95% CI: $-4.77, -0.77$) could impact on the COVID-19 transmission in Sri Lanka. We found that every 1 m/s (meter per second) rise in the velocity of wind at 10 m of height from the surface will decrease COVID-19 reported cases by 3 people per day. Similarly, minimum temperature with 5 days ago ($\beta = -4.75$, 95% CI: $-1.51, -37.15$) could negatively and maximum temperature with 12 days ago ($\beta = 5.1$, 95% CI: $0.06, 10.14$) could positively impact on COVID-19 for Afghanistan. We also found that every 1 °C increase in minimum temperature could reduce the confirmed case by 5 people per day. Rainfall and the ambient particulate matter PM 2.5 had a negative impact on COVID-19 incidence for Pakistan while minimum temperature had a positive impact. Likewise, the maximum temperature for Bangladesh and rainfall and maximum wind speed for India had negative impact on the transmission of COVID-19. More detailed results were found in Table A.2.

Table 1

Summary of COVID-19 confirmed case counts along with daily climate and air quality parameters (maximum PM 2.5 and maximum wind speed) for five South Asian countries until 31 August 2020.

	Afghanistan	Bangladesh	India	Pakistan	Sri Lanka
Daily confirmed case (number of person)					
Minimum	0.00	0.00	0.00	0.00	0.00
Maximum	915	4019	85,687	12,073	300
Mean \pm SD	200.9 \pm 237.3	1768 \pm 1321	17,168 \pm 23,448	1574 \pm 1852	13.99 \pm 28.02
Rainfall (mm per day)					
Minimum	0.00	0.00	0.00	0.00	0.00
Maximum	54.38	69.85	153.08	92.56	32.80
Mean \pm SD	1.80 \pm 6.17	9.06 \pm 12.53	5.89 \pm 14.67	5.73 \pm 15.23	2.60 \pm 4.20
Relative humidity (%)					
Minimum	10.73	30.48	10.93	24.67	57.46
Maximum	92.84	94.80	94.68	86.79	90.10
Mean \pm SD	43.32 \pm 22.19	72.79 \pm 19.93	52.77 \pm 27.01	55.15 \pm 12.58	75.14 \pm 7.42
Minimum temperature at a day ($^{\circ}$ C)					
Minimum	-9.43	17.62	8.43	-0.89	17.33
Maximum	18.38	28.19	30.90	25.46	25.47
Mean \pm SD	8.15 \pm 6.44	25.10 \pm 2.49	22.39 \pm 4.92	15.95 \pm 6.51	22.53 \pm 1.68
Maximum temperature at a day ($^{\circ}$ C)					
Minimum	3.38	28.33	24.38	9.93	27.04
Maximum	36.55	40.82	45.40	40.39	37.01
Mean \pm SD	23.73 \pm 9.12	33.21 \pm 3.23	34.34 \pm 5.44	29.26 \pm 6.52	31.69 \pm 2.38
Surface pressure (kPa)					
Minimum	77.86	99.11	94.68	85.60	97.14
Maximum	79.18	101.29	97.02	87.33	98.12
Mean \pm SD	78.47 \pm 0.27	100.41 \pm 0.42	95.91 \pm 0.48	86.47 \pm 0.40	97.60 \pm 0.26
Maximum PM2.5 at a day (μ g per m ³)					
Minimum	53	65	124.83	94.25	25
Maximum	284	412	309.09	315.25	178
Mean \pm SD	142.15 \pm 40.77	180.58 \pm 57.56	200.50 \pm 34.82	162.54 \pm 35.98	98.99 \pm 39.72
Maximum wind speed at a day (m/s)					
Minimum	1.45	1.44	1.50	2.74	1.76
Maximum	12.89	12.62	15.52	13.08	12.83
Mean \pm SD	6.38 \pm 2.34	5.46 \pm 2.22	5.82 \pm 2.13	5.97 \pm 1.62	5.81 \pm 2.34

4. Discussion

We examined the effects of weather on COVID-19 transmission in South Asian countries using the ARIMAX model approach. Our study shows that weather variables have significant positive or negative effects on COVID-19 infections. However, the findings don't seem to be consistent across the selected countries in South Asia. For example, the maximum wind speed was significantly negatively correlated with the COVID-19 transmission only in India and Sri Lanka. In addition, the temperature had significant positive and negative impact on the transmission in four countries in South Asia, excluding India.

We found that maximum wind speed had a significant negative impact on COVID-19 transmission which is in line with some previous

studies (Ahmadi et al., 2020; Islam et al., 2020; Zoran et al., 2020). However, this finding was opposed to some recent studies (Bashir et al., 2020; Li et al., 2020; Menebo, 2020) where they claimed that there was no correlation between wind speed and COVID-19 transmission. Moreover, in the previous outbreak of influenza virus or severe acute respiratory syndrome (SARS), or middle east respiratory syndrome coronavirus (MERS-CoV), the wind speed regarded as one of the key factors that promote the transmission of SARS, MERS and influenza (Altamimi and Ahmed, 2020; Chan et al., 2011; Chong et al., 2020; Peci et al., 2019). Moreover, previous studies (van Doremalen et al., 2020; Bourouiba, 2016) claimed that COVID-19 may be airborne which can stabilize in aerosols for up to 3 h and increase the risk of transmission through aerosols. The risk of COVID-19 spread might be more in closed

Table 2

ARIMA model selection using Bayesian Information Criteria (BIC).

		ARIMA (2,1,2) ^a	ARIMA (3,1,2)	ARIMA (0,1,2)	ARIMA (0,1,3)	ARIMA (2,1,1)
Afghanistan	BIC	2211.3	2213.92	2212.77	2209.24^b	2215.26
Bangladesh	BIC	2523.07	2509.44	2516.99	2514.47	2518.71
Pakistan	BIC	3109.51	3113.12	3127.28	3100.41	3109.75
Sri-Lanka	BIC	2024.37	2029.48	2029.80	2023.64	2019.19
		ARIMA (2,2,3)^c	ARIMA (2,2,2)	ARIMA (1,2,1)	ARIMA (0,2,1)	ARIMA (0,2,3)
India	BIC	3948.38	3984.59	4016.41	4019.78	3983.12

The bold numbers indicate the lowest BIC values of the respective countries.

^a Here, ARIMA (2,1,2) means autoregressive term of order 2, moving average term of order 2 and first difference was taken to make the series stationary.

^b All the selected best ARIMA models need to satisfy the three conditions: lowest BIC, significant parameter estimation and no autocorrelation in residual analysis. Though ARIMA (0,1,3) has lowest BIC value, it provides insignificant parameter estimation. That's why we move for 2nd lowest BIC value and ARIMA (2,1,2) satisfies all the three conditions.

^c For India 2nd difference was taken to make the COVID confirmed series trend and mean stationary.

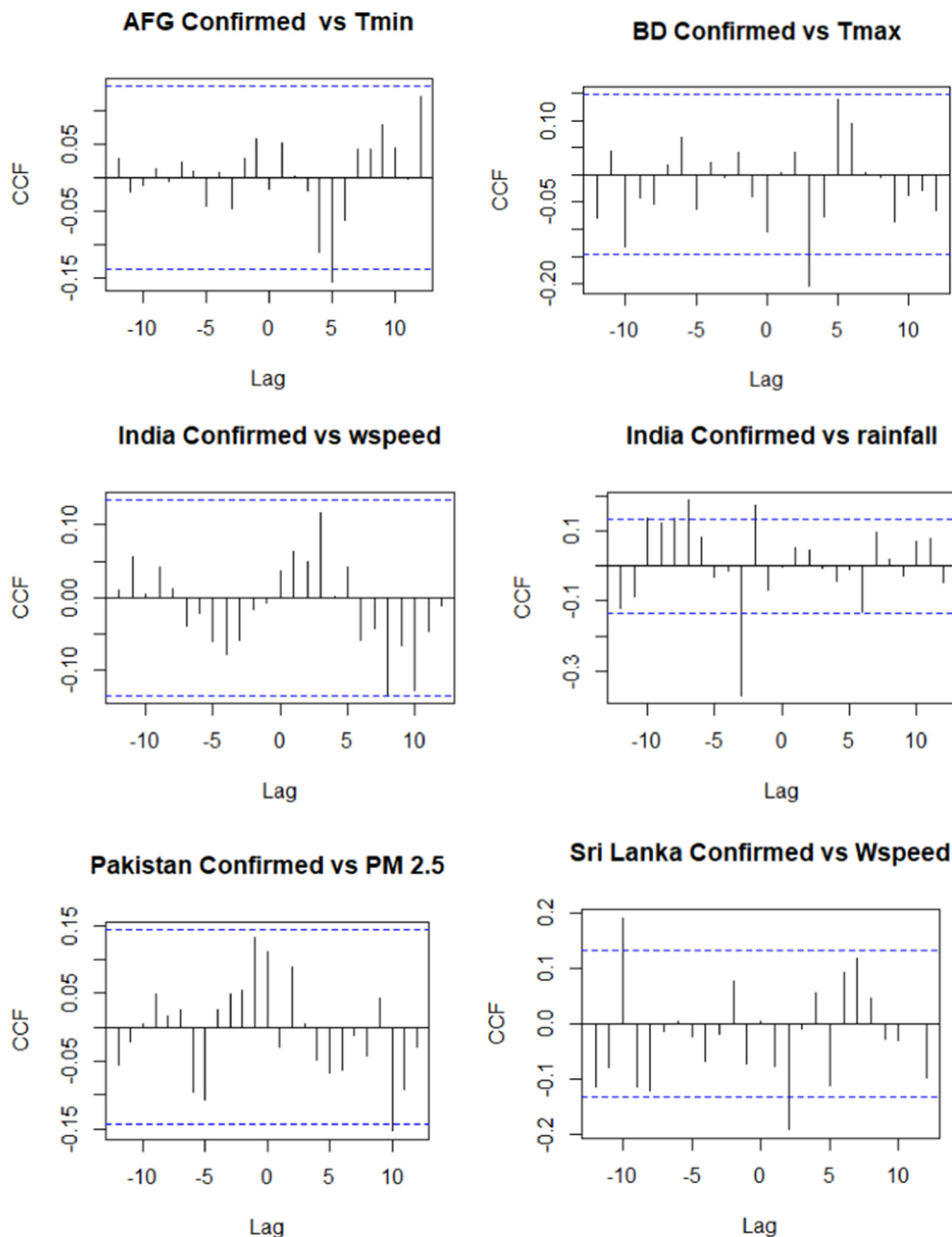


Fig. 3. Cross-correlation between COVID-19 confirmed cases and weather variables. Here AFG means Afghanistan, BD means Bangladesh, Wspeed means maximum wind speed, Tmin is Minimum Temperature, Tmax is Maximum Temperature.

places with low wind speed because in low wind speed particle density of infectious droplets is much higher which can favor the spread of COVID-19 virus in the environment.

Our analyses also showed that temperature had a significant positive and negative impact on the transmissibility of COVID-19 in four south Asian countries except for India. Menebo (2020), Bashir et al. (2020) and (A. Gupta et al., 2020) also reported similar findings that temperature had a significant positive correlation with COVID-19. Furthermore, some other studies reported inverse relationship (Guo et al., 2020; Islam et al., 2020; Li et al., 2020; Rahman et al., 2020; Shi et al., 2020; Y. Wu et al., 2020) or no relation (Jamil et al., 2020; Poirier et al., 2020) between temperature and incidence of COVID-19. As the south Asian countries have high population density with low income including less aware of the transmission, people often break the lockdown for their livelihood on shiny days. And this may be one of the reasons for

the positive relationship between temperature and confirmed cases. In that case, temperature plays one of the key indirect factors for COVID-19 transmission.

We did not find any association of COVID-19 transmission with relative humidity and surface pressure. Shi et al. (2020) also obtained similar findings that there was no significant correlation between COVID-19 incidence and absolute humidity. However, some other studies (S. Gupta et al., 2020; Li et al., 2020; Ma et al., 2020; J. Wang et al., 2020; Y. Wu et al., 2020) found opposite results that there exists an association of COVID-19 with relative humidity and pressure.

Air pollutants included particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}^3$ (maximum PM 2.5) had a significant negative impact on COVID-19 only in Pakistan. Ma et al. (2020) found similar findings in Wuhan, China that the mortality counts due to COVID-19 were negatively correlated with PM 2.5 and PM 10. Zoran et al. (2020) and

Table 3
Estimated parameters with confidence interval of significant weather parameters of the ARIMAX models.

	Afghanistan	Bangladesh	India	Pakistan	Sri Lanka
Factors	ARIMAX (2,1,2)	ARIMAX (3,1,2)	ARIMAX (2,2,3)	ARIMAX (0,1,3)	ARIMAX (2,1,1)
Max. temperature (3)		−30.52* (−60.24, −0.78)			
Max. temperature (12)	5.10* (0.06, 10.14)				
Min. temperature (5)	−4.75* (−8.95, −0.56)				
Min. temperature (10)				49.13* (0.424, 97.84)	3.51* (0.12, 6.9)
Rainfall (6)			−48.64* (−80.17, −17.09)		
Rainfall (10)				−14.44* (−23.03, −5.86)	
Rainfall (12)				12.56* (4.09, 21.03)	
Wind speed (2)					−2.77* (−4.77, −0.77)
Wind speed (8)			−209.45* (−369.13, −49.77)		
PM 2.5 (10)				−4.69* (−8.28, −1.10)	

Note: PM 2.5 means maximum atmospheric particulate matter with diameter less than 2.5 and * means significant at 5% level.

Bashir et al. (2020) reported opposite findings (positive correlation) that a high level of air pollution has a significant impact on the increased rates of confirmed COVID-19 cases. It is obvious that higher concentrations of air pollution could increase the risk of respiratory virus infection (Horne et al., 2018). But interestingly, our results showed that COVID confirmed cases were associated with a decrease in the average concentration of air pollutants (PM 2.5), which could be a reflection of higher rainfall at the same time, as rainfall washes away pollutants from the atmosphere and for Pakistan, we also reported the significant effect of rainfall. Similar type of argument was also made by Silva et al. (2014) where they showed that Severe Acute Respiratory Infection (SARI) cases were negatively associated with air pollutants. Hence, we argue that the effect of air pollutants on COVID transmission depends on the impact of other relevant factors (rainfall) and the effect varies depending on city, region, and the specific pollutants under investigation.

Rainfall had a significant negative impact on COVID-19 transmission in India and Pakistan, also had positive impact in Pakistan (at lag 12) which is in line with (A. Gupta et al., 2020; Menebo, 2020; Sobral et al., 2020) and opposite with some recently published studies (Ahmadi et al., 2020; Bashir et al., 2020; Li et al., 2020; Tosepu et al., 2020). The possible reason for the negative correlation is that rainfall rate contributes to the accumulation and washout process of aerosols and microbial bio-aerosols (Bacteria, viruses, fungi) implying that viruses could not have longer residence times in the atmosphere and, consequently will not be able to disperse further. Another hypothetical justification might be that people often stay home on rainy days, which also could reduce the transmission. We also found that rainfall at lag 12 had an impact on COVID-19 transmission which means that 12 days previous values of rainfall might have effect on today's COVID confirmed cases. This happens because of time-dependency, each value depends on previous time point values. As values tend to decrease/increase over time, it is obvious to get some correlation at low/high lag values. Our study also reported an increasing trend of rainfall, and this might be a possible reason for getting such a relatively long days (12 days) effect on virus transmission.

Some nobilities of our study need to be addressed; firstly, we used the most recent datasets till 31 August 2020 of five South Asian countries in our study which reflect the overall COVID-19 situation of South Asia. Secondly, a wide variety of climate and air pollutant variables were used to assess their impact on COVID-19 transmission. Third, as there exists a substantial climatic and geographical variation

among the countries, we examined the country-specific climate and air variables impact on COVID-19 transmission. And finally, a well-defined time series ARIMAX model was applied to serve the purpose of the study.

Despite the numerous advantages of this study, there exist some shortcomings too. We have mentioned the significance of wind speed but it is quite difficult to determine. Wind direction can also be an influential factor but due to lack of data we cannot examine its effect on virus transmission. We did not consider socio-economic (age, sex, population density, countries development, and health indices), clinical (respiratory infection among family members, co-morbidity, co-infections), lifestyle factors (smoking, quarantine, massive lockdown, social distancing) and other important factors like the health system, the enforcement and implication of regulation, school closure, restrictions on people movement such as travel restriction, intensive contact tracing followed by quarantine and isolation etc. (Tang et al., 2020) in our study which may have a greater impact on the virus transmission of COVID-19. We excluded Nepal, Bhutan, and the Maldives from our study because, at the time of this study, the infection rate is much slower, which can result in the inconsistent estimator of our implemented time series model. That's why, we took the five most vulnerable South Asian countries to identify the real scenario of the impact of weather on COVID-19 transmission.

5. Conclusions

Our study shows that not only environmental temperature but also maximum wind speed, rainfall, and air pollutants (maximum PM 2.5) play an essential role in the transmission of COVID-19 in South Asia. However, the findings don't seem to be consistent across the countries, and therefore, it is difficult to conclude that the dependency of COVID-19 transmission cannot be explained by weather parameters alone. Current and future incidence of COVID-19 cannot only be controlled by medical research, social distance, research, and practices of wearing masks and strict lockdown, but also need to develop environmental policies such as reducing the emission of particulate compounds, improving air quality and ecosystem.

Ethical approval and consent to participate

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CRediT authorship contribution statement

Md. Sabbir Hossain: Conceptualization, Writing - original draft, Software, Methodology, Formal analysis, Visualization, Writing - review & editing, Validation. **Sulaiman Ahmed:** Data curation, Software, Visualization, Writing - review & editing. **Md. Jamal Uddin:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: There are no financial, personal, political, academic, or other relations that could lead to a conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.143315>.

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