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Impact of climate on COVID-19 transmission: A study over Indian states

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ABSTRACT

Coronavirus Disease-2019 (COVID-19) started in Wuhan province of China in November 2019 and within a short time, it was declared as a worldwide pandemic by World Health Organisation due to the very fast worldwide spread of the virus. There are a few studies that look for the correlation with infected individuals and different environmental parameters using early data of COVID-19 but there is no study so far that deals with the variation of effective reproduction number and environmental factors. Effective reproduction number is the driving parameter of the spread of a pandemic and it is important to study the effect of various environmental factors on effective reproduction number to understand the effect of those factors on the spread of the virus. We have used time-dependent models to investigate the variation of different time-dependent driving parameters of COVID-19 like effective reproduction number and contact rate using data from India as a test case. India is a large population country that is highly affected due to the COVID-19 pandemic and has a wide span of different temperature and humidity regions and is ideal for such study. We have studied the impact of temperature and humidity on the spread of the virus of different Indian states using time-dependent epidemiological models SIRD, and SEIRD for a long time scale. We have used a linear regression method to look for any dependency between the effective reproduction number with the relative humidity, absolute humidity, and temperature. The effective reproduction number shows a negative correlation with both relative and absolute humidity for most of the Indian states, which are statistically significant. This implies that relative and absolute humidity may have an important role in the variation of effective reproduction number. Most of the states (six out of ten) show a positive correlation while two (out of ten) show a negative correlation between effective reproduction number and average air temperature for both SIRD and SEIRD models.

1. Introduction

The first case of COVID-19 was reported in India on January 30, 2020 (Delhi, 2020). Till October 10, 2021, India had 33.9 million total confirmed cases which were highest in Asia (Worldometer, 2020a) and the second-highest in the world (Worldometer, 2020a). During the above-mentioned period, India had 33.2 million recoveries, and 0.45 million were deceased (Worldometer, 2020a). Study with India is interesting as it is the world’s second-largest population with about one-sixth of the world’s total population (Worldometer, 2020b).

The second wave of COVID-19 started in India on February 11, 2021. The second wave had a significant impact with daily cases nearly four times than during the first wave peak (Ranjan et al., 2021). In India, the second wave was caused mainly by the double mutant variant. Currently, four mutant Coronavirus variants are dominant: a) Brazil variant [P.1 (P.1)] (MoHFW, 2021b), b) Indian variant [B.1.617], c) South Africa variant [S01Y.V2 (B.1.351)], and d) UK Variant [VOC 202012/01 (B.1.1.7)] (MoHFW, 2021a). WHO cautioned that the Indian variety, B.1.617, was rapidly spreading in India, accounting for more than 28% of positive test samples. The Indian strain (B.1.617) of SARS-CoV2 was found to be more infectious compared to other SARS-CoV-2 variants (WHO et al., 2021).

The spread of an epidemic depends on a large number of factors. Earlier, it was found that humidity is one of the driving factors to explain the seasonality of influenza (Shaman and Kohn, 2009). Similar seasonal variability would be expected for COVID-19 and other coronaviruses like SARS. The spread of COVID-19 (SARS-CoV-2) was found to be correlated with temperature and latitude (Poole, 2020). A study of the seasonality of many other viruses, like seasonal Influenza, suggests that the cool season in the northern hemisphere favours disease propagation more than the warm season in the northern hemisphere (Poole, 2020). Earlier, it was shown that 50% of the influenza virus transmission variability can be explained by absolute humidity but a detailed study was not possible for limited data (Shaman and Kohn, 2009).
Meteorological parameters (temperature, relative humidity, and absolute humidity) may play an important role in influencing infectious diseases such as severe acute respiratory syndrome (SARS) and influenza.

At the beginning of the spread of the COVID-19 disease, it was widely believed that summer will cause the virus to reduce (Bukhari and Jameel, 2020). Results of other coronaviruses (such as SARS coronavirus) also indicated that the virus may be less effective with rising temperature and humidity (Chan et al., 2011). A rigorous study is necessary with a large amount of data to explore the effect of temperature and humidity on the spread of COVID-19.

Several social or non-meteorological factors could influence the correlation study between meteorological factors and COVID-19 transmissions, such as governmental interventions, social interactions, lockdowns, herd immunity, vaccinations, population density, personal hygiene, defece mechanisms, and cultural activities. Different studies focused on the impact of social interaction on COVID-19 spread (Bontempi and Coccia, 2021; Bontempi et al., 2021; Calbi et al., 2021; Block et al., 2020; Oraby et al., 2021). Well-timed lock-downs have been found to split the peak of hospitalizations into two smaller distant peaks, extending the overall pandemic duration. Lock-down is the most rigorous public health measure which can be taken to minimize contact rate and viral transmissions in a community (Oraby et al., 2021). It was found that during the second wave, the 2021 assembly election played a major role in the COVID-19 spread rate in India (Manik et al., 2021).

In the present paper, we investigate the influence of average air temperature, absolute humidity, and relative humidity on the effective contact rate and reproduction number of COVID-19. There are a few studies that look for the correlation with infected individuals and different environmental parameters using early data of COVID-19 (Arumugam et al., 2020; Chiyomaru and Takimoto, 2020; Pirouz et al., 2020; Notari, 2021; Sajadi et al., 2020) but so far there is no study that deals with the variation of effective reproduction number and environmental factors. Effective reproduction number is the driving parameter of the spread of a pandemic and it is important to study the effect of various environmental factors on the effective reproduction number to understand the effect of those factors on the spread of the virus. Our study is unique as we deal with time-dependent models and look for the impact of temperature and humidity on effective reproduction number.

We have done a rigorous study for different Indian states which are strongly affected during the second wave of COVID-19. Coronavirus spread has been influenced by a variety of parameters including the use of masks, personal hygiene, social distance, vaccination, etc. We have assumed that these factors remained constant for these states throughout the study and that their impact on the result is minimal. India also represents a wide variety of temperatures and humidity regions, which is ideal for our study. In this paper, we have looked at the variety of different driving parameters of the pandemic like effective contact rate ($\beta$) and effective reproduction number ($R_0$) using time-dependent mathematical models SIRD and SEIRD for different Indian states.

In Sect. 2, we summarise different mathematical models of the pandemic. Sect. 2.1 carries a brief introduction of the SIRD model. A short introduction of the SEIRD model is given in Sect. 2.2. We have discussed the data analysis and methodology in the Sect. 3. In Sect. 4, we present our findings. The temperature dependence of the effective reproduction number is discussed in the Sect. 4.1 and the humidity dependence of the effective reproduction number $R(t)$ is discussed in Sect. 4.2. In Sect. 5, we discuss our findings, and in Sect. 6 we summarise our results.

2. Mathematical models

Different mathematical models are designed to simulate the effect of the disease from different perspectives (Gupta et al., 2020a; Piccololimi and Zama, 2020; Pribylova and Hajnova, 2020; Ndiaye et al., 2020; Notari, 2021). These help us to get an idea about the spread rate of a disease over the population. We have used the time-dependent epidemiological models SIRD and SEIRD. The spread rate depends on a large number of parameters such as mean incubation time (Bhattacharjee, 2020; Baum, 2020), mean infectious period, social distancing, and risk of international spread (Bogoch et al., 2020; Zhao et al., 2020). The most important part of these models is to calculate the basic reproduction number ($R_0$) which is the contagiousness of the disease. $R_0$ is defined as the average number of people who can be affected by a single infected person over a course of time. $R_0 > 1$ indicates that the spread is increasing, $R_0 = 1$, indicates that the spread is stable and $R_0 < 1$, indicates that the spread is expected to stop. We have studied the effective reproduction number $R(t)$ for India using different models. We have also studied the evolution of $R(t)$ using the same models for different individual states of India.

2.1. SIRD model

There are several models for studying contagious disease transmission in a large population. The simplest compartmental model that can explain the evolution of an outbreak at the population level is the Susceptible-Infected-Recovered (SIR) model. The SIRD model (Ndiaye et al., 2020; Manik et al., 2021) is the extended version of the SIR model. We have used this model to study different time-dependent parameters like effective reproduction number ($R$), contact rate ($\beta$), recovery rate ($\gamma$), and mortality rate ($\delta$). At any time $t$, $S(t)$ be the total number of susceptible individuals, $I(t)$ be the total number of infected individuals, $R(t)$ be the total number of recovered, and $D(t)$ be the total number of deceased individuals. The SIRD model assumes that the population is mixed homogeneously. Though India is a big country, it may be safely assumed that the mixing was nearly homogeneous. The population is classified into four categories at time $t$: susceptible, infectious, recovered, and deceased. The total population, $N$, is assumed to remain constant during the study. Natural birth and death are often ignored in simple compartmental models because the spread rate of COVID-19 is typically considerably faster than the dynamics of birth and death. Furthermore, it is supposed that everyone who is exposed to the virus becomes infected immediately, with no latent period between exposure and infection.

Different compartments of the SIRD model are shown in Fig. 2. The infant entered susceptible class $S$ once the maternal antibodies no longer existed in the body. Since a susceptible has enough contact with an infective to allow transmission, they are known as an infective class $I$, which means they are infectious in the sense that they can transmit the virus. Once the infectious phase is elapsed, the individual falls into one of two classes: $R$, which is made up of people who gained immunity through infection, or $D$, which is made up of deceased people. Here, $\beta$ is the contact rate and $\gamma$ is the recovery rate and $\delta$ is the mortality rate. $s(t)$, $i(t)$, $r(t)$ and $d(t)$ can be expressed in fractional form:

$$s(t) = \frac{S(t)}{N}, \quad i(t) = \frac{I(t)}{N}, \quad r(t) = \frac{R(t)}{N}, \quad d(t) = \frac{D(t)}{N} \quad (1)$$

from the conservation law,

$$s(t) + i(t) + r(t) + d(t) = 1 \quad (2)$$

SIRD model can be expressed by following set of differential equations.

$$\frac{ds(t)}{dt} = -\beta(t)s(t)i(t) \quad (3)$$

$$\frac{di(t)}{dt} = \beta(t)s(t)i(t) - [\gamma(t) + \delta(t)]i(t) \quad (4)$$

$$\frac{dr(t)}{dt} = \gamma(t)i(t) \quad (5)$$
Fig. 1. Variation of daily confirmed and deceased individuals for India with 3 days rolling mean. The shaded region shows the time for which the whole study is conducted during the second wave of COVID-19 in India.

Fig. 2. The schematic diagram showing different compartments of SIRD, and SEIRD model. $\beta$ is the contact rate, $\gamma$ is the recovery rate, $\sigma$ is the incubation period, and $\delta$ is the mortality rate.
\[
\frac{dd(t)}{dt} = \delta(t)i(t)
\] (6)

from the equation (4), we may write
\[
\beta_n = \frac{1}{s_n} \left[ \gamma_{n+1} + (\gamma_n + \delta_n - 1) i_n \right]
\] (7)

We use equation (5) to find \(\gamma_n\)

\[
\gamma_n = \frac{r_{n+1} - r_n}{i_n}
\] (8)

Now we use equation (6) to find \(\delta_n\)
\[
\delta_n = \frac{d_{n+1} - d_n}{i_n}
\] (9)

The effective reproduction number \(R(t)\) can be expressed as

**Fig. 3.** Variation of different driving parameters of the pandemic with time for different Indian states. \(\gamma(t)\) is the recovery rate, \(\beta(t)\) is the effective contact rate, \(\delta(t)\) is the mortality rate and \(R(t)\) is the effective reproduction number.
Environmental Research 211 (2022) 113110

\[ R(t) = \frac{\beta}{\gamma + \delta} \]  
\[ \text{(10)} \]

In Fig. 3, we have shown a variety of different parameters for the SIRD model for a few selected Indian states. In the second, third, and fourth row, the variation of effective contact rate \( (\beta_{\text{SIRD}}(t)) \), the variation of recovery rate \( (\gamma_{\text{SIRD}}(t)) \), and the variation of mortality rate \( (\delta_{\text{SIRD}}(t)) \) are shown. The fifth row represents the variation of effective reproduction number \( (R_{\text{SIRD}}(t)) \) for the SIRD model.

\[ \text{Fig. 3. (continued).} \]

2.2. SEIRD model

The Susceptible-Exposed-Infected-Recovered-Deceased (SEIRD) model (Li, 2018) is the extended version of the SEIR model. At any time \( t \), \( S(t) \) be the total number of susceptible individuals, \( E(t) \) be the total number of exposed individuals, \( I(t) \) be the total number of infected individuals, \( R(t) \) be the total number of recovered individuals, and \( D(t) \) be the total number of deceased individuals from the epidemic. In the SEIRD model, we have considered the average incubation period of \( 1/\sigma \) as a constant. We presume that the individuals who recovered from the
disease can not become susceptible again.

Various compartments of the SEIRD model are shown in Fig. 2. The Exposed (E) compartment in the SEIRD model is an extension to the SIRD model. The susceptible (S) moves into the exposed compartment (E) when a susceptible individual comes across significant interaction with an infective individual (I). The individual enters the class I at the end of the latent phase and becomes capable to spread the infection. Finally, at the end of the infectious time, the person moves to either the recovered compartment R or the deceased compartment D (for detail, see section 2 of Manik et al. (2021)).

The parameter β is the product of the average number of contacts per person and per unit time by the probability of disease transmission in contact between susceptible and infectious individuals. γ is the recovery rate and δ is the mortality rate. The compartment E of the exposed individuals in the SEIRD model makes the model slightly more delicate. The SEIRD model is a compartmental model used to understand the mathematical modeling of infectious diseases in a large population. If N is the total population size then in fraction form

\[ s(t) = \frac{S(t)}{N}, e(t) = \frac{E(t)}{N}, i(t) = \frac{I(t)}{N}, r(t) = \frac{R(t)}{N}, d(t) = \frac{D(t)}{N} \]  

(11)

From the conservation of the total number of individuals, we have the relation

\[ s(t) + e(t) + i(t) + r(t) + d(t) = 1 \]  

(12)

These quantities change by discrete amounts but if the minimal possible change is relatively low, we can consider \( s(t), i(t), r(t), d(t) \) as differentiable functions. For any time \( t \geq 0 \), the SEIRD model can be expressed by the differential equations

\[ \frac{ds(t)}{dt} = -\beta(t)s(t)i(t) \]  

(13)

\[ \frac{de(t)}{dt} = \beta(t)i(t)i(t) - \sigma e(t) \]  

(14)

\[ \frac{di(t)}{dt} = \sigma e(t) - [\gamma(t) + \delta(t)]i(t) \]  

(15)

\[ \frac{dr(t)}{dt} = \gamma(t)i(t) \]  

(16)

\[ \frac{dD(t)}{dt} = \delta(t)i(t) \]  

(17)

We use the discrete form of equations (13)–(17).

We use equation (14) to find \( \beta_n \)

\[ \beta_n = \frac{e_{n+1} - e_n + \sigma e_n}{s_n i_n} \]  

(18)

We use equation (16) to find \( \gamma_n \)

\[ \gamma_n = \frac{r_{n+1} - r_n}{i_n} \]  

(19)

Now we use equation (17) to find \( \delta_n \)

\[ \delta_n = \frac{d_{n+1} - d_n}{i_n} \]  

(20)

The effective reproduction number \( R(t) \) can be given by

\[ R(t) = \frac{\beta_n}{\gamma_n + \delta_n} \]  

(21)

In Fig. 3, we have shown the variation of different parameters for the SEIRD model for a few selected Indian states. In the second and third row, the variation of effective contact rate (\( \beta_{SEIRD}(t) \)) and the variation of recovery rate (\( \gamma_{SEIRD}(t) \)) are shown. The fourth row shows the variation of mortality rate (\( \delta_{SEIRD}(t) \)) and the fifth row shows the variation of effective reproduction number (\( R_{SEIRD}(t) \)) for the SEIRD model.

3. Data analysis and methodology

We have used the COVID-19 data maintained by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University to track reported cases of Coronavirus in real-time (Dong et al., 2020). The
time-series data of different Indian states can be accessed from this source.\(^1\) We have obtained weather data from “World Weather Online” using a python based API from February 1, 2021 to October 10, 2021. We have taken state population data from the “India Census” site.\(^2\) We have used standard python packages i.e., Numpy, Scipy, Pandas, Matplotlib, Epitools, Epitools (Manik et al., 2022a) for the entire work. Since environmental variables are not expected to have an immediate effect on COVID-19 cases, we have acquired weather data including temperature and relative humidity 7 days before the reported cases. We have also calculated absolute humidity, the actual amount of water vapour in the atmosphere, depending on the air temperature, \(T\) (in °C) and relative humidity, \(RH\) in % (Auler et al., 2020). The absolute humidity \((AH;\text{ in } g/m^3)\) is the weight of water vapour per unit volume of air and is estimated using the Clausius-Clapeyron equation and can be described as follows (Gupta et al., 2020b).

\[
AH = \frac{6.112 \times e^{\frac{17.56 \times RH}{237.35 + T}} \times 2.1674}{273.15 + T}
\]  

(22) where \(AH\) corresponds to absolute humidity, \(RH\) is the relative humidity, and \(T\) is the average temperature.

We have selected the ten most affected Indian states for which the total confirmed COVID-19 cases were maximum during the time-span of COVID-19’s wave in India (February 2, 2021 to October 10, 2021). The lower threshold of total confirmed individuals was 0.56 million during the above-mentioned period for those selected states. We have studied the variation of confirmed, recovered, and deceased individuals for Indian states Maharashtra, Kerala, Karnataka, Tamil Nadu, Andhra Pradesh, Uttar Pradesh, West Bengal, Delhi, Rajasthan, and Gujarat. These states belong to different corners of the country with wide variability for different meteorological parameters like temperature and humidity and formed an ideal sample of states to study the impact of temperature and humidity on the spread of the virus. In Fig. 3, the first row shows the variation of the number of infected, recovered, and deceased individuals with time, the second row shows the variation of effective contact rate \(\beta(t)\) with time, the third row shows the variation of recovery rate \(\gamma(t)\), the fourth row shows the variation of mortality rate \(\delta(t)\) and the fifth row shows the variation of effective reproduction number \(R(t)\) for different Indian states.

In the SEIRD model, there is more fluctuation for few states in the plot of effective contact rate and effective reproduction number in Fig. 3, compared to the SIRD model. The results from both SIRD and SEIRD are significant and show a similar type of trend. Since the SEIRD model has an additional compartment (Exposed) in comparison to the SIRD model, it is more realistic and shows relatively more variability compared to SIRD model.

Fig. 4 shows the variation of average temperature \(\text{T_{av}}\), relative humidity \((RH)\), and absolute humidity \((AH)\) for different Indian states for which the study is executed. The figure shows a wide range of temperature and humidity since selected states represent different regions of the country.

4.1. Temperature dependence of \(R(t)\)

We have studied the dependence of effective reproduction number \(R(t)\) on temperature for different Indian states. The linear regression method is used to find the correlation and the regression coefficient \(R^2\). Table 1 shows the result of the correlation study using linear regression method for different models during the study period. The positive sign indicates the correlation between effective reproduction number \((R(t))\) and average temperature \((T_{av})\) with a positive slope and the negative sign indicates a correlation between \(R(t)\) and temperature with a negative slope. The correlation with negative slope indicates that the effective reproduction number \(R(t)\) will decrease with the increase of the temperature. For the SIRD model, two states Delhi and Rajasthan show a negative correlation between \(R(t)\) and \(T_{av}\), which indicates that for these two states the COVID-19 spread is reduced by increasing temperature. Six states out of ten, show a positive correlation between \(R(t)\) and \(T_{av}\) for both SIRD and SEIRD models, which implies that effective reproduction number increases with the increase of average air temperature. For the states of Gujarat and Uttar Pradesh the correlation is not conclusive.

The first column of Fig. 5 represents the variation of the effective reproduction number \(R(t)\) with average temperature \(T_{av}\) for different Indian states (Maharashtra, Kerala, Karnataka, Tamil Nadu, Andhra

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1. https://data.covid19india.org/.
2. https://www.indiacensus.net/.
The variation of $R(t)$ with $T_{av}$ is estimated for two different time-dependent models SIRD and SEIRD. A positive correlation is found for the states of West Bengal, Tamil Nadu, Maharashtra, Andhra Pradesh, Kerala, and Karnataka for both models, whereas the states Delhi, and Rajasthan shows a negative correlation between $R(t)$ and $T_{av}$.

For the state of Gujarat and Uttar Pradesh, the correlation results are not conclusive. The state of Gujarat shows a positive correlation with $T_{av}$ for the SIRD model and a negative correlation for the SEIRD model, which is less significant than the SIRD model. For Uttar Pradesh, the SIRD model shows a positive correlation and the SEIRD model shows a negative correlation, both correlations are statistically less significant (p-value $>0.05$).

Humidity plays a crucial role as a driving environmental parameter on the spread of a virus. We have investigated whether there is any dependence of relative and absolute humidity on the spread rate of COVID-19. We have studied the correlation of effective reproduction number $R(t)$ with relative humidity ($RH$) and absolute humidity ($AH$) with a seven-day running average. We have used the linear regression method to look for any correlation between $R(t)$ with $RH$ and $AH$. We find out the correlation coefficient $R^2$. We have summarized the result of

Fig. 4. Variation of average temperature, relative humidity (RH) and absolute humidity (AH) with time for different Indian states.
Table 1
Value of regression coefficient $R^2$ with p-value using different models for different Indian states from $\langle R(t) \rangle$ vs $T_{av}$ plot with seven days running average. The ‘+’ sign implies positive correlation and ‘−’ sign implies negative correlation between $\langle R(t) \rangle$ and $T_{av}$.

| State        | $R^2_{SIRD}$ (%) | p-value | $R^2_{SEIRD}$ (%) | p-value |
|--------------|------------------|---------|-------------------|---------|
| Delhi        | 3.60 (−)         | 0.003   | 3.68 (−)          | 0.002   |
| Gujrat       | 1.26 (+)         | 0.078   | 0.55 (−)          | 0.244   |
| Karnataka    | 51.97 (+)        | 9.72 × 10^{-4} | 31.68 (+) | 5.89 × 10^{-22} |
| Kerala       | 7.26 (+)         | 1.85 × 10^{-5} | 5.27 (+) | 0.28 × 10^{-3} |
| Andhra Pradesh | 28.86 (+)    | 8.59 × 10^{-20} | 8.63 (+) | 2.75 × 10^{-6} |
| Maharashtra  | 2.31 (+)         | 0.017   | 0.60 (+)          | 0.226   |
| Rajasthan    | 0.25 (−)         | 0.430   | 2.14 (+)          | 0.022   |
| Tamil Nadu   | 14.37 (+)        | 7.9 × 10^{-10} | 13.08 (+) | 5.16 × 10^{-9} |
| Uttar Pradesh| 2.58 (+)         | 0.012   | 1.51 (−)          | 0.054   |
| West Bengal  | 25.26 (+)        | 3.8 × 10^{-17} | 13.32 (+) | 3.64 × 10^{-9} |

Another worldwide study with 100 nations (up to March 18, 2020) with wide temperature variation from −33.9 to 34.3°C, suggested a negative correlation between daily COVID-19 cases and temperature (−10°C to 10°C) for provinces of China (Shi et al., 2020). Several studies investigated the effect of humidity on the spread of the virus, but the results were inconclusive for few countries. There was no definite correlation between humidity and COVID-19 transmission in studies from Africa, Indonesia, Jakarta, New York, the USA, and a global study of 100 nations (Meyer et al., 2020; Bashir et al., 2020; Adekunle et al., 2020; Josepu et al., 2020). A weak positive correlation was found between average relative humidity and COVID-19 cases in Saudi Arabia (Alkhawaled et al., 2020). A significant positive correlation between relative humidity and new COVID-19 cases was reported for the United States (Chien and Chen, 2020). A negative correlation between the relative humidity and COVID-19 cases was reported for Spain (Paez et al., 2021), where transmission reduced by 3% for every 1% increase in humidity. Earlier, it was found that high temperature and humidity reduce the COVID-19 confirmed cases, deaths and improve recovery (Sarkodie and Owusu, 2020). UV index, wind speed, pressure, and precipitation also may have an impact on virus transmission (Manik et al., 2022b). Several studies emphasise the correlation between air pollution and COVID-19 transmission (Lembo et al., 2021; Conticini et al., 2020; Al Huraimel et al., 2020). A significant correlation was found between different air pollutant agents and greenhouse gas elements with the cumulative positive number of cases and deaths (Lembo et al., 2021).

We have used the time-dependent models SIRD and SEIRD to study the evolution of different time-dependent driving parameters of a pandemic like effective reproduction number and effective contact rate for different Indian states which are strongly affected by COVID-19. Most of the states show a negative correlation between $\langle R(t) \rangle$ and $RH$, which implies that the relative humidity might be playing a role to control the spread of the virus.

For the state of Kerala, we have found a positive correlation between $\langle R(t) \rangle$ and $AH$ for both the models SIRD and SEIRD. For the state of Delhi, the negative correlation significance is relatively low for the SIRD model but a positive correlation is observed with effective reproduction number. All ten states show a negative correlation between $\langle R(t) \rangle$ and $AH$, which implies that the effective reproduction number decreases with an increase in absolute humidity. Absolute humidity may be playing a role to control the spread of the virus.

5. Discussion

Earlier a mixed result was found between correlation of COVID-19 transmission and temperature using the early phase of the COVID-19 data in different global locations. A positive correlation was found for several studies in New York (Bashir et al., 2020) and Jakarta (Josepu et al., 2020). A negative correlation was observed for multiple worldwide studies (Arunagam et al., 2020; Chiyomaru and Takemoto, 2020; Pirouz et al., 2020; Notari, 2021; Sajadi et al., 2020; Wu et al., 2020; Xie and Zhu, 2020) in California (Gupta et al., 2020b), Italy (Livadiotis, 2020), Ghana (Idrisu et al., 2020), Japan (Ujie et al., 2020), Spain (Abdollahi and Rahbaralam, 2020; Tobias and Molina, 2020), and China (Oliveiros et al., 2020; Qi et al., 2020; Shi et al., 2020; Shi and Kumar, 2020). For the countries like Nigeria (Taiwo and Fashola, 2020), Spain (Briz-Redon and Serrano-Arocá, 2020), Iran (Ahmadi et al., 2020; Jahangiri et al., 2020), and in a worldwide study (Jamal et al., 2020) no correlation was found.

Global research of 166 nations (excluding China) found a negative correlation between temperature and COVID-19 cases, with a temperature increase of 1°C resulting in a 3.08% drop in cases (Yu et al., 2020).
Fig. 5. Correlation between the effective reproduction number \( R(t) \) and 7 days moving average of the different meteorological parameters. The best fitted linear regression lines are shown with the orange (SEIRD) and the blue (SIRD) colors. The shaded region for both the fitted regression lines depict 95% confidence interval. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
humidity. All of the states except Tamil Nadu and Kerala show a negative correlation between the absolute humidity and effective reproduction number for the SIRD model. The state of Tamil Nadu shows a positive correlation with a high p-value, which is statistically less significant. For the SEIRD model in the state of Delhi, Kerala, and Tamil Nadu, the correlation between the effective reproduction number and...
Therefore, countries should put more emphasis on healthcare policies that account for the majority of the variation in disease transmission. Temperature and absolute humidity may play a role in epidemic spread, but their impact is marginal when compared to other social factors such as social interaction, governmental interventions, lock-downs, population density, herd immunity, personal hygiene, migration patterns, and relative and absolute humidity of different Indian states. We have calculated the effective reproduction number and relative and absolute humidity for the Indian states. We have investigated the correlation between climate indicators and COVID-19 pandemic: a comprehensive study from Saudi Arabia. Informatics in Medicine Unlocked 20, 100418. https://doi.org/10.1016/j.imu.2020.100418.

Table 2
The summary of regression coefficient $R^2$ with p-value using different models for different Indian states from $\hat{R}(t)$ vs $\hat{R}$ plot with seven days running average. The ‘+’ sign implies positive correlation and ‘−’ sign implies negative correlation between $\hat{R}(t)$ and $\hat{R}$.

| State         | $R^2_{SEIRD}$ (%) | p-value  | $R^2_{SEIRD}$ (%) | p-value  |
|---------------|-------------------|----------|-------------------|----------|
| Delhi         | 1.02 (-)          | 0.013    | 7.13 (+)          | 2.20 x 10^{-5} |
| Gujarat       | 13.71 (-)         | 2.05 x 10^{-9} | 0.80 (-)         | 0.160    |
| Karnataka     | 40.01 (-)         | 6.67 x 10^{-29} | 26.30 (-)       | 6.61 x 10^{-18} |
| Kerala        | 0.83 (+)          | 0.154    | 1.17 (-)          | 0.089    |
| Andhra Pradesh| 32.70 (-)         | 9.25 x 10^{-23} | 24.73 (-)       | 9.99 x 10^{-17} |
| Maharashtra   | 22.91 (-)         | 1.71 x 10^{-15} | 20.10 (-)       | 1.43 x 10^{-13} |
| Rajasthan     | 21.78 (-)         | 1.04 x 10^{-14} | 2.85 (-)        | 0.008    |
| Tamil Nadu    | 7.07 (-)          | 2.39 x 10^{-5}  | 9.83 (-)        | 5.14 x 10^{-7} |
| Uttar Pradesh | 20.04 (-)         | 1.57 x 10^{-13} | 0.60 (-)        | 0.225    |
| West Bengal   | 12.75 (-)         | 8.27 x 10^{-9}  | 13.21 (-)       | 4.23 x 10^{-9} |

Table 3
The summary of regression coefficient $R^2$ with p-value using different models for different Indian states from $\hat{R}(t)$ vs $\hat{AH}$ plot with seven days running average. The ‘+’ sign implies positive correlation and ‘−’ sign implies negative correlation between $\hat{R}(t)$ and $\hat{AH}$.

| State         | $R^2_{SEIRD}$ (%) | p-value  | $R^2_{SEIRD}$ (%) | p-value  |
|---------------|-------------------|----------|-------------------|----------|
| Delhi         | 2.78 (-)          | 0.008    | 2.99 (+)          | 0.006    |
| Gujarat       | 18.67 (-)         | 1.29 x 10^{-12} | 3.19 (+)       | 0.005    |
| Karnataka     | 22.01 (-)         | 7.19 x 10^{-15} | 15.79 (-)      | 9.88 x 10^{-11} |
| Kerala        | 4.56 (+)          | 0.74 x 10^{-3}  | 1.58 (+)        | 0.049    |
| Andhra Pradesh| 17.44 (-)         | 8.43 x 10^{-12} | 24.39 (-)      | 1.55 x 10^{-16} |
| Maharashtra   | 32.60 (-)         | 1.1 x 10^{-22}  | 31.73 (-)       | 5.3 x 10^{-22} |
| Rajasthan     | 27.67 (-)         | 6.58 x 10^{-19} | 6.07 (-)       | 9.4 x 10^{-15} |
| Tamil Nadu    | 1.16 (+)          | 0.091    | 0.16 (+)          | 0.533    |
| Uttar Pradesh | 22.12 (-)         | 6.10 x 10^{-15} | 2.57 (-)       | 0.011    |
| West Bengal   | 5.18 (-)          | 0.0003   | 8.06 (-)         | 6 x 10^{-6} |

absolute humidity is positive, the rest of the states show a negative correlation. The p-value for the states Kerala and Tamil Nadu is high which implies less statistical significance.

6. Conclusion
We have looked for the evolution of different driving parameters of a pandemic using time-dependent epidemiological models SIRD and SEIRD for different Indian states. We have studied the correlation between effective reproduction number with average temperature, relative humidity, and absolute humidity of different Indian states. We have found that most of the Indian states show a negative correlation between effective reproduction number and relative and absolute humidity for time-dependent models SIRD and SEIRD, which implies that humidity may have an impact on the spread of the virus. The correlation between temperature and effective reproduction number suggests that for most of the Indian states effective reproduction number increases with the increase of average air temperature. There also exist several factors like personal hygiene, vaccination, social interaction, etc., which also play a crucial role in the spread of the virus. Environmental variables, particularly temperature and humidity, may play a role in epidemic spread, but their impact is marginal when compared to other social factors such as social interaction, governmental interventions, lock-downs, population density, herd immunity, personal hygiene, migration patterns, defence mechanisms and so on. Temperature and humidity alone cannot account for the majority of the variation in disease transmission. Therefore, countries should put more emphasis on healthcare policies and vaccination.

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We are giving consent for publication of this article in Environmental Research.

Availability of data and material
We have used data from https://data.covid19india.org and https://github.com/CSSEGISandData/COV219.

Code availability
Not applicable.

Author contribution
Souvik Manik: Validation, Resources, Formal analysis, Visualization, Investigation, Data curation, Writing - review & editing.
Manoj Mandal: Conceptualization, Methodology, Validation, Formal analysis, Visualization, Investigation, Writing - original draft.
Sabyasachi Pal: Conceptualization, Methodology, Investigation, Visualization, Writing - review & editing, Supervision, Project administration.
Subhradeep Patra: Data curation, Visualization, Formal analysis.
Suman Acharya: Data curation, Visualization.

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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