Indirect response of the temperature, humidity, and rainfall on the spread of the COVID-19 over the Indian monsoon region

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Abstract

This paper examines the role of the meteorological variable on the spread of the ongoing pandemic coronavirus disease 2019 (COVID-19) across India. COVID-19 has created an unprecedented situation for public health and brought the world to a standstill. The COVID-19 has caused more than 1,523,242 deaths out of 66,183,029 confirmed cases and around the world till the first week of December 2020. We have examined the surface temperature, relative humidity, and rainfall over five cities namely Delhi, Mumbai, Kolkata, Bengaluru, and Chennai severely affected by COVID-19. It is found that the prevailing southwest (SW) monsoon during the pandemic has acted as a natural sanitizer in limiting the spread of the virus. The day-to-day variation of the meteorological parameters and COVID-19 cases clearly demonstrate both surface temperature and relative humidity play a vital role in the indirect transport of the virus. Our analysis reveals that the majority of the COVID-19 cases fall within the surface temperature ranging from 24°C to 30°C and relative humidity ranging from 50–80%. At a given temperature, COVID-19 cases show a large dependency on the relative humidity which attributes those coastal environments were more prone to infections. Wavelet transforms coherence analysis of the daily COVID-19 cases with temperature and relative humidity reveal a significant coherence within 8 days.

Introduction

Coronavirus disease 2019 (COVID-19) was first identified in Wuhan, China, in December 2019 as an infectious disease caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) (Li et al., 2020). SARS-CoV-2 is a single-stranded positive-sense Ribonucleic acid (RNA) virus (Lu et al., 2020), extremely contagious nature, registered cases across the globe to date (as of December 05, 2020) are 66,183,029 (<https://www.worldometers.info/>). SARS-CoV-2 belongs to the same family as Severe Acute Respiratory Syndrome (SARS) and Middle East Respiratory Syndrome (MERS) of Coronavirus (CoVs) (Chen et al., 2020). These viruses cause common cold to severe respiratory disease and lead to death (Huang et al., 2020). SARS-CoV-2 is transmitted primarily to a susceptible through the human-to-human, droplet, airborne, fomite, and animal-to-human contact (Li et al., 2020). The indirect transmission paths such as aerosols, droplet, and contaminate fomite are found to be highly influenced by the surface temperature, relative humidity, Ambient humidity, solar radiation (Asyary & Veruswati, 2020; Nazari Harmooshi et al., 2020; Prata et al., 2020; Wang et al., 2020; Yuan et al., 2020; Zhu et al., 2020). However, the significance of airborne transmission and its different pathways is still uncertain (Jayaweera et al., 2020) due to limited data. In general, the infected persons viral particles were spread through breathing, cough, conversations, and sneezing (Yongjian et al., 2020). Setti et al. (2020) reported that SARS-CoV-2 – RNA was identified in the free atmospheric aerosols over Italy. The World Health Organization (WHO) postulated that the viral particles are below 5µm as aerosols and above 5µm as droplets (Jayaweera et al., 2020). The larger droplets tend to fall on the surface due to the gravitational pull while the smaller particles linger and float into the air (Feng et al., 2020). Thus, aerosols pose a higher risk of widespread COVID-19 disease even far away from their point of origin (Van Doremalen et al., 2020).

The diameter of SARS-CoV-2 virus ranges from 65 to 125 nm (Shereen et al., 2020) which can be blended with Aitken and accumulation modes of aerosol particles that may result into an enhancement of the widespread of COVID-19 disease. In general, 80–90 % of human respiratory particles are less than 1 μm (Papineni & Rosenthal, 1997) which can travel a maximum of 4.5 m and 7 m during cough and sneezing, respectively (Loh et al., 2020).

Numerous studies were corroborated COVID-19 with meteorological parameters. Pani et al. (2020) reported relative humidity and temperature favors the spread of COVID-19 disease, and it is negatively correlated with atmospheric boundary layer height (ABL), wind speed, and ventilation coefficient. It has been observed that lower air temperature and higher humidity lead to prolonged viability of virus in contaminated Fomite (Kim et al., 2007). Xie and Zhu (2020) reported the spread of SARS-CoV-2 is positively correlated at 3°C of ambient temperature. (Zhu et al., 2020) reported a positive correlation against absolute humidity with SARS-CoV-2. Yuan et al. (2020) reported the mortality rate of COVID – 19 disease is found to be positive with relative humidity. It is to be noted that with the increase of the temperature beyond 38°C and relative humidity greater than 95 %, viruses lose their viability in the tropical environment (Chan et al., 2011). It is reported that indirect transmission was more effective when compared to direct transmission due to India's unique geographical location and seasonal patterns (Neher et al., 2020). However, a few studies (Gupta et al., 2020) reported that SARS-CoV-2 spread is ineffective with temperature increases. Thus, the role of the metrological parameters on the spread of COVID-19 is under debate (Zaitchik et al., 2020).

Such contradictory findings on the role of the meteorological parameters mainly appear due to different methods of analysis. These studies have performed mainly linear rank correlation analysis to establish the link between metrological variables and COVID-19 cases which is actually nonlinear variables leading to a low confidence in statistical significance. Thus, in-depth examination of the role of the meteorological parameters in the spread of SARS-CoV-2 transmission over the different regions of the globe is required for future projection handle pandemic like COVID-19 facing today.

In response to the COVID-19 pandemic, India, world's second-largest populous country, is severely affected among other Asian countries. Although India had overcome several outbreaks such as SARS, swine flu, Nipah Virus, etc., COVID-19 was the most severe among them. As of December 05, 2020, India witnessed about 95,90,086 confirmed cases, 1,39,433 deaths, and 90,38,081 recovered cases. Although several studies have yielded wealthy information on the link between meteorological parameters and COVID-19 cases, most of the studies suffered due to inappropriate methodology and hypothesis (Zaitchik et al., 2020) as mentioned earlier. For example, Babu et al. (2020) reported the positive (negative) correlation between daily COVID-19 cases and temperature (relative humidity) during March to June over Delhi; however, Gupta et al. (2020) contradicting the results of Babu et al. (2020) and reported no correlation between COVID-19 cases with any weather parameters over Delhi and other 8 major affected cities. Sasikumar et al. (2020) reported the cities with higher CO₂ emissions over India are vulnerable to COVID-19 infections. At an early phase of the COVID-19 cases during the Indian summer season (March to May), the surface temperature increases linearly and reaches its maximum value, which was coincided with

increasing COVID-19 cases resulting into a strong correlation. However, such seasonal variation in the temperature is unlikely to be related with increasing CO₂ emissions attributing to COVID-19 cases. Though increasing in CO₂ is major reason for the increasing the temperature, direct attribution of the higher CO₂ emission to the increase in temperature within a season and increasing COVID-19 spread may misguide the public health settings such as imposing or lifting the lockdown. It is noteworthy to mention that COVID-19 severely affected the Karnataka region, which is known to have lower emission of CO₂ than other less affected regions (e.g., Gujarat) (Garg et al., 2017). In the present study, we hypothesize that Indian summer monsoon rainfall was an important factor in curtailing the spread of the COVID-19 spread over the Indian region. Also, we have employed a non-linear wavelet approach to examine the link between surface meteorological variables such as temperature, relative humidity and rainfall on COVID-19 spread over five severely affected metropolitan cities, Delhi, Mumbai, Kolkata, Bengaluru, and Chennai as well as overall India.

Datasets And Methodology

2.1 COVID -19 cases data

The pandemic COVID 19 data over Indian cities obtained from the official website of the Ministry of Health and Family Welfare Govt. of India (<https://www.mohfw.gov.in/>, <https://www.mygov.in/corona-data/covid19-statewise-status>). Information on cities wise detail data available from 26 Apr 2020 to date. Therefore, in this study, we have used daily reported COVID 19 cases data for severely affected metropolitan cities (Delhi, Mumbai, Kolkata, Bangalore, and Chennai) and over India from 26 Apr 2020 to 5th Dec 2020.

2.1 Weather data

To understand the role and influence of temperature and relative humidity on COVID-19 spread over Indian cities, we obtained daily surface temperature and relative humidity data from the automatic weather station (AWS) from IMD stations over Delhi, Mumbai, Kolkata, Bangalore, and Chennai during 22 March 2020 from 5 December 2020. To investigate the role of the meteorological parameters on the COVID-19 spread over entire Indian region, we have used daily surface temperature and relative humidity data from ERA5 over the period March – December 2020.

2.2 GPM-IMERG - Rainfall data

The daily rainfall data was obtained from Integrated Multi-satellite Retrievals for Global Precipitation Mission (GPM) (IMERG). The GPM is a joint mission between the National Aeronautics Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) that was successfully launched on 27 February 2014. The IMERG estimates the precipitation by using Goddard Profiling Algorithm (GPROF2017) and Combined Ku Radar-Radiometer Algorithm (CORRA). The IMERG products are available in Early, Late, and Final with the latency of 4 h, 12–14 h, and 3.5 months, respectively (Arshad et al., 2021; Huffman et al., 2015). IMERG early and late runs used for real-time monitoring

application such as floods, irrigation, and Final run is used for research purpose. In this study, we have used level 3 version 6 Daily (GPM_3IMERGDL) Final data with a spatial resolution of $0.1^\circ \times 0.1^\circ$.

2.4 Methodology

We have obtained daily reported new confirmed COVID-19 cases from the cumulative COVID – 19 cases. Note that the daily number of the cases from the cumulative cases are obtained by successive difference. Figure 1 depicts the number of COVID-19 cases for 28 Indian States and 8 Union Tertiaries (UTs). We have shown the total number of cases for each States and UTs as the color gradient. It can be seen that highest number (between 1-2 million) of the cases was reported over Mumbai in the Maharashtra state followed by four South Indian States Andhra Pradesh, Karnataka, Tamil Nadu and Kerala. In the North India, Delhi (UT), Utter Pradesh, and West Bengal was most affected. Rest of the States and UTs of India was less effected and number of the confirmed cases was less than 0.2 million. We have selected the five most affected metropolitan cities Delhi, Mumbai, Kolkata, Bengaluru and Chennai. The geographical location, population densities, cumulative COVID-19 cases, recovery cases and deceased cases are given in Table 1.

Table 1. Details of Geographic locations, population density and the COVID-19 cases for selected Indian cities and over whole Indian region as of 05 December 2020

S. No	Region	Latitude ($^\circ$ N)	Longitude ($^\circ$ E)	Population density (/ km^{-2})	Cumulative COVID-19 confirmed cases	Cumulative COVID-19 recovery cases	Cumulative COVID-19 deceased cases
1	Delhi	28.70	77.1	27,730	589544	553292	9574
2	Mumbai	19.0	72.87	20,980	285267	259435	10964
3	Kolkata	22.57	88.36	24,306	110737	102167	2665
4	Bangalore	12.97	77.59	4,381	373291	349929	4176
5	Chennai	13.08	80.27	26,553	217204	209997	3868
6	India	20.59	78.9	382	9644529	9099946	140220

Wavelet transform coherence (WTC) analysis

To study the association between daily confirmed COVID-19 cases with daily average surface temperature and relative humidity, we have employed the Wavelet transform coherence (WTC) analysis instead of correlation analysis. The WTC technique is an excellent tool to establish a relationship between non-linear time series (Alola & Kirikkaleli, 2020). It allows the investigation of the co-movement between daily reported COVID-19 cases and meteorological variables in both the time and frequency domain. Therefore,

this wavelet approach can simultaneously provide a lead-lag relationship and both positive and negative associations between time-series datasets. To perform WTC analysis, we utilized "Morlet wavelet" to transform the data to continuous wavelet as:

$$\psi_{k,f}(t) = \frac{1}{\sqrt{(h)}} \psi\left(\frac{t-k}{f}\right), k, f \in \mathbb{R}, f \neq 0 \quad (1)$$

Where k estimates the time function of the wavelet and f controls the variation in frequency from shorter to longer scale of the time series. From equation (1), the continuous wavelet transform is reconstructed for the time $p(t)$, and frequency $q(t)$ is denoted as:

$$W_p(k, f) = \int_{-\infty}^{\infty} p(t) \frac{1}{\sqrt{(f)}} \psi\left(\frac{t-k}{f}\right) dt \quad (2)$$

Finally, we employed the WTC analysis by the framework of Torrence and Compo (1998), which is given as:

$$R^2(k, f) = \frac{|c(f^{-1} W_{pq}(k, f))|^2}{c(f^{-1} |W_p(k, f)|^2) c(f^{-1} |W_q(k, f)|^2)} \quad (3)$$

In equation (3) the time and smoothing process is captured by C with the values ranging between

$0 \leq R^2(k, f) \leq 1$, where zero represents no coherence, and one refers to the perfect coherence. To estimate the significance level of the coherence, we performed a Monte Carlo simulation between daily reported COVID-19 cases with daily average temperature and relative humidity.

Results And Discussion

3.1 Daily variations of meteorological parameter and COVID-19 cases

Day-to-day variation of the COVID-19 cases, surface temperature, relative humidity, and rainfall over Delhi, Mumbai, Kolkata, Bangalore, and Chennai are shown in Figures 2 – 6, respectively.

Over Delhi, the temporal pattern of COVID-19 cases shows three significant peaks during June, September, and November, which can be considered as three phases of COVID-19 outbreaks. During the first phase, the daily COVID-19 cases gradually increase from March, and it peaks to ~ 3,700 cases during the last week of June and falling less than 500 cases at the end of July (Fig 2a). The temporal variation of the first phase covers both pre-monsoon (March-May) and monsoon months (June -August) during which temperature (relative humidity) appears to be in phase (out of phase) with COVID-19 cases. Note that

surface temperature reaches maximum up to 38°C at the end of May and gradually falls during monsoon months due to the onset of the southwest (SW) monsoon season. The relative humidity is found to be ~ 40 - 50 % during April – May, which increases to ~ 55-80 % during June – July (Fig. 2c). At the higher temperature and lower humidity, the virus evaporates faster from respiratory droplets and forms bio-aerosols (Jayaweera et al., 2020), which can linger up in the air for a longer duration and drift to a longer path in the presence of the higher wind speed (Yan et al., 2019). Thus, the airborne transmission is dominant during March-May, which appears to be more venerable than the droplet transmission. Because the smaller aerosols can quickly reach the lung by inhalation that could have been the primary reason for the higher number of the COVID-19 cases during pre-monsoon months despite of the complete lockdown. Whereas decrease in the COVID-19 cases during June - July appears to be mainly associated with frequent rainfall events (Fig 2d). The wet removal due to rainfall appears to act as a natural sanitizer resulting in a negative effect on the airborne transmission. Though during the rainfall season, the drop in the surface temperature and rise in the relative humidity may have the possibility of the droplet mode of virus transmission (Marr et al., 2019), however, we observed that the COVID-19 cases were remain sustained during June-July. In the second phase (August– mid-October), the daily COVID-19 cases start gradually increasing from August and become maximum during September and decrease from mid-September – mid-October. During this second phase, the surface temperature slightly increased, relative humidity starts falling dawn, and SW monsoon was withdrawn, resulting in increased COVID-19 cases. In general, the evaporation rate of the virus droplets is low at the lower temperature and intermediate relative humidity; thus, the virus remains either as a liquid or semi-solid phase resulting in its prolonged viability (Marr et al., 2019). Therefore, larger virus-laden droplets on the contaminated surface result to sustain a longer period and contributing to an increased probability of an increased number of the cases evident during mid-August to mid-September. Such similar situation was also reported over Brazilian cities (Auler et al., 2020). The decrease in the COVID-19 cases from mid-September appears related to the reduction of relative humidity (RH< 40%) and drop in temperature in the post-monsoon months. Airborne transmission becomes favorable in the presence of the low moisture content and high temperature in the atmosphere; however, viruses lose viability in a shorter time scale (~ 3 hours) (Jayaweera et al., 2020). Therefore, it is evident increase in relative humidity plays a vital role in the spread of COVID-19. During third phase (mid-October to November), the day-to-day variation of the COVID-19 cases are much higher when compared to the previous two phases. In this phase, variation in the relative humidity appears similar to variability in the COVID-19 cases. Lowen et al. (2007) reported that the cold and dry conditions favor many other infectious diseases like influenza, which increases the possibility higher number of COVID cases. Despite the droplet transmission, the massive rise in COVID-19 cases over a short period during October – November suggests overwhelming direct transmission (human to human contact, Fomite) compared to indirect transmission. This indicates that human movement during cold and dry seasons increases the susceptibility of the COVID-19 outbreaks.

Over Mumbai, the temporal pattern of COVID-19 cases indicates the two significant broad peaks during May-June and September-October, which are considered here as the two phases COVID-19 outbreaks covering the period of pre-monsoon to SW monsoon months (March to August) and covering SW

monsoon to northeast (NE) monsoon months (September to November). Similar to Delhi, an increase in the surface temperature with relative humidity ranging between 50-60% (intermediate value) favors airborne transmission leading to a steep increase in COVID-19 cases over Mumbai (Figure 3). With the onset of SW monsoon, a sudden drop in temperature (from 31°C to 25°C) and rise in relative humidity (from 60 to 90%) are observed due to heavy rainfall incidence during the first week of June. Due to the SW monsoon rainfall, the COVID-19 cases were reduced and limited to ~ 2000 or lesser daily cases; otherwise, could have been a higher number of the cases. Thus, rainfall acts as a natural sanitizer as mentioned earlier, it limits airborne transmission due to frequent wet deposition, leading to a decline in the COVID-19 cases. However, the possible risk of spread remains higher for Mumbai like populous city, due to sea breeze and strong wind during SW monsoon season as even light breeze (1- 3 m / s) can transport the virus droplets by 1.8 m (Feng et al., 2020). This could be a possible reason that Mumbai does not show a significant reduction in the COVID -19 cases even though frequent rainfall was observed during the SW monsoon season. As Mumbai is a coastal station while Delhi is a land-locked station, the former is more susceptible to the virus's faster spread due to the sea breeze (Feng et al., 2020). In the SW monsoon's withdrawal phase, the increasing surface temperature and intermediate relative humidity condition favor the COVID spread during the second phase. However, the sudden rise in COVID-19 cases during September is mainly associated with direct transmission. The second phase of the COVID-19 cases was not as prolonged as the first phase over Mumbai. The sudden drop in COVID cases is observed during the month of October – November. It is known that decreasing relative humidity at high temperature resulting to the shorter timescale of virus viability and hence to the lower number of cases.

Over Kolkata, the day-to-day variation of the COVID-19 cases also depicts two significant broad peaks during July-August and October-November. The observed two peaks are considered here as the two phases of outbreaks similar to Mumbai. However, the number of the COVID-cases is smaller than the previous stations. Kolkata has significantly less day-to-day COVID cases (< 200) during the first phase from March to June. A rapid increase in cases was later observed, and maximum cases were found at the end of July; however, it decreases soon within a month during August. The lower temperature and high humidity prevailed over Kolkata during the SW monsoon season (June – September). Such an environmental condition is not favorable for airborne transmission; however, the sudden increase in cases was observed during the month of July. This is strongly associated with direct transmission due to communities begin to reopen further it suggests poor monitoring of human mobility during the first unlock down period. During post-monsoon months, mostly the environment was found to be a dry and cold condition which led to prolonging stability of the virus period and results second wave propagation. It is to be noted if the public isolation policy lifting of lockdown instead of June, it would have been continued till July the massive increase in cases has been avoided in Kolkata. Therefore, it suggests the public health setting, like imposing or lifting of lockdown should be implemented based on the local condition instead of nationwide.

Bengaluru sets one extreme example of the COVID-19 spread, unlike previous cases mentioned. When major metropolitan cities were reporting very high daily COVID-19 cases, Bengaluru remains less affected, and fewer cases are reported. However, unexpectedly, the cases started to pick up from mid-June and

reached maximum daily cases of ~ 5000 during the end of September. Over Bengaluru, warm temperature and low relative humidity during Aril-May favor airborne transmission. During this period, the daily reported COVID-19 cases were less than ~200, similar to as observed over Kolkata. Later, during the months from June to September, the temperature was observed to be ~ 22-23°C and relative humidity ~ 70-90%, suggesting that evaporation of virus droplet could be delayed due to low temperature and high humidity, resulting in virus persistence for the longer duration lead to a higher number of cases over Bengaluru(Auler et al., 2020). Earlier studies also confirmed that higher relative humidity is prone to a constructive health hazard(Auler et al., 2020) for any kind of infectious outbreak. In addition to this, a strong low-level jet during the SW monsoon could have increased the spread of the virus over a larger scale. As the number of cases was rapidly increasing, direct transmission might have been one of the leading factors, as mentioned earlier. During the post-monsoon season, the COVID-19 cases suddenly start decreasing, and surface temperature and relative humidity also decrease to transition towards cold and dry weather. Though relative humidity shows a large fluctuation associated with isolated rainfall, it has not significantly affected the COVID-19 cases except a little amplification.

Over Chennai, both SW and NE monsoons prevail, unlike all the other cities mentioned earlier. We observed a clear day-to-day variation of the COVID-19 cases associated with in-phase variation with surface temperature and out of phase variation with RH. During the months of May-June, the temperature and humidity vary between 31 to 33°C and ~ 60%, respectively. This environmental condition favors the production of more aerosol nuclei and spread Via the wind movement of longer tracks; these nuclei may drift further. It results in a higher number of cases even during complete public isolation during the period of lockdown. Later, the onset of the SW monsoon rainfall leading to a decline in the COVID cases. Noticeably, the maximum number of the new cases was observed end of June, and later, there were heavy rainfalls for nearly about 4-5 days which removes the infected bioaerosols from the atmosphere and reducing the chances of the droplet mode transmission, which leads to decrease in less than 1000 cases per day, however, remains prolonged till the end of September due to the warmer and intermediate humidity condition. As similar to the SW monsoon, the NE monsoon rainfall leading to further decrease in cases during the months of October to December. In addition, strict implementation of the Government guidelines and support of the public led to eradicating the virus infection to a low level.

3.2 COVID-19 cases as a function of surface temperature and relative humidity

Figure 7 shows the density plot of the COVID-19 cases as the function of surface temperature and relative humidity for the two-land locked stations, Delhi and Bengaluru, and three coastal stations, Mumbai (west coast of India) and Kolkata and Chennai (east coast of India). We observed that the number of the cases generally follows in the line of an inverse relationship between surface temperature and relative humidity; however, not always. Over Delhi, Mumbai, and Chennai, the COVID-19 cases were found roughly increasing with an increase in temperature and a decrease in relative humidity. Whereas over Bengaluru and Kolkata, the COVID-19 cases were found roughly increasing with a decrease in temperature and an increase in relative humidity. Over Delhi and Kolkata, maximum cases are found with low temperature (20-28°C) and intermediate relative humidity (40-80%). Over Mumbai, a significant number of cases falling in

the range of relatively higher temperature (28-31°C) and intermediate relative humidity (40-70%). At the high surface temperature, virus structural proteins and the genomic structure may have been changed, which may cause the deactivation of the virus in a shorter time scale (~3 hours)(Aboubakr et al., 2020), resulting in a fewer number of COVID-19 cases over Bengaluru and Kolkata. Higher cases over these stations with high humidity could be due to the larger size of infected droplets that would have converted to a smaller size after evaporation and remains as aerosol nuclei and spread through the air.

At an early phase of COVID-19, during pre-monsoon season March – May, when high surface temperature and low relative humidity were prevailing over almost throughout India and human mobility was completely restricted by imposing nationwide lockdown since 22nd March 2020, the spread of COVID-19 was mainly through airborne transmission. However, during June – October, after lockdown lifted, a surge in COVID-19 cases appears due to direct transmission. Note that the relative humidity had played a vital role in virus viability. From Fig 7 it is clearly observed that a higher number of COVID-19 cases are reported at intermediate (55 – 80%) and higher RH (> 80%) with a temperature between 22-28°C across all the cities. Aboubakr et al. (2020) reported, during low/moderate T with intermediate/ high RH results, SARS COV 2 viruses remain longer time on the surfaces (over stainless steel ~ 7 days, copper ~ 4 days, and glass ~ 5.8 days).

3.3 Role and Influence of T and RH

We observed that the relationship between the COVID-19 cases and meteorological parameters (surface temperature and relative humidity) is not linear. Hence, performing the linear regression and correlation analysis to derive their relationships will be misleading the results. To better understand the relationships between COVID-19 spread as a function of temperature and relative humidity, we have performed wavelet transformation coherence (WTC) analysis which provides the correlation coefficients at an appropriate lag. Figure 8 shows the WTC analysis between daily COVID-19 cases and surface temperature and relative humidity for Delhi, Mumbai, Kolkata, Bengaluru, and Chennai. Colorbar indicates the magnitude of the correlation coefficients. The right and left arrowheads indicate the positive and negative correlation with meteorological parameters. The thick black contour lines indicate a 95% of confidence level. The arrow-headed right up and left down indicate the time-series of meteorological variables leading the COVID time-series. . The u shaped curved line refers to the cone of influence where the wavelet power is affected due to discontinuity which is not considered for the analysis.

The time and frequency domain of the WTC analysis of the COVID-19 cases with the surface temperature over Delhi shows a significant coherence within 0-4 days frequency bands during the first week of July, the first week of September, last week of October, the first week to mid of November. We also observed significant coherence within 4-8 days during the last week of May, the first week of July, and mid-September to the first week of October. During the last week of May and the first week of July, we observed a negative correlation (0.9) with arrow sign 'left-indicating COVID-19 cases leading the temperature. Note that such a situation is not a plausible one. Though this result is mathematically correct however physical interpretation would be rather difficult to explain because it has been understood

that changes in the background metrological condition play an indirect role in the spread of the COVID-19 cases (Zaitchik et al., 2020). It is to be noted that the indirect effect COVID-19 pandemic on the weather and climate cannot be ruled out due to the slow rate of anthropogenic activities during the worldwide lockdown. However, such analysis and interpretations are beyond the scope of the present study. From mid-September to the first week of October, we observed positive correlation coefficients (0.9) with arrow sign “right-up,” indicating temperature is leading the COVID-19 cases.

Over Mumbai, significant coherence was observed within 0-8 days frequency band during the second week and end of May, end of June, the last week of July, first and second week as well as the end of August, and mid of October. We observed positive correlations between temperature and COVID-19 cases with temperature leading (right-up arrow sign) during the last week of July, the second week of August, and the end of August. In contrast, negative correlations between temperature and COVID-19 cases with temperature leading (left-down arrow sign) are observed during the first week of August. Note that a positive (negative) correlation between temperature and COVID-19 cases observed during the second week of May (mid-October) with COVID cases leading the temperature is not a possibility, as mentioned earlier. We also observed the coherence within 16-32 days frequency bands with a positive correlation where the temperature is leading to COVID cases during mid-August to the end of October.

Over Kolkata, prominent coherence is observed within 4-8 days frequency bands during June and 8-16 days frequency bands during September. However, during June, COVID is leading to temperature and hence discarded as mentioned earlier. During September, a negative correlation is observed between temperature and COVID-19 cases with temperature leading (left-down arrow sign). Note that the second wave over Kolkata was initiated during September, indicating that the decrease in the surface temperature acted as the favorable condition of droplet transmission to a massive increase in the COVID cases during October.

Over Bengaluru, significant coherence is observed within 4-8 days frequency bands during the first week of July and the first week of October. During the first week of July, the temperature is negatively correlated and leading to the COVID-19 cases as expected. However, during the first week of October, the temperature is positively correlated at no lead /lag to COVID-19 cases. The in-phase coherence between temperature and COVID-19 cases mean that suspected patients would have reported when the temperature goes high even though they would have been affected earlier in contrast to the first week of July. We also observed coherence for 8-16 days during the second half of August, which indicates that temperature and COVID-19 cases are negatively correlated and leading to the COVID-19 cases. For 8 – 32 days period during the first week of October to the first week of November, we observed a negative correlation with COVID leading for the lower period and a positive correlation with temperature leading for a higher period. However, such a long period may occur due to change in season from SW monsoon to post-monsoon.

Over Chennai, the significant coherence observed for 0-8 days frequency bands during the last week of July and the first week of October and mid-October as well as 32-64 days frequency bands during

September-October. During the last week of July and the first week of October, we observed a downward and left downward arrow indicating the negative correlation with temperature leading to COVID-19 cases. However, during mid-October, we observed both positive and negative correlations with COVID-19 leading the temperature. As mentioned earlier, the temperature is positively correlated to COVID-19 cases during September-October could be due to seasonal changes in the temperature.

Similarly, WTC analysis between COVID-19 cases and relative humidity for the five cities are also carried out, as shown in Fig 9. The coherence between COVID-19 cases with relative humidity shows mostly opposite to the coherence between COVID-19 cases and temperature except for a little variation frequency bands and the level of significance. Similar to the temperature, the relative humidity also shows significant coherence within 0-4, 4-8, and 8-16 days frequency bands. It is to be noted that the observed periodicity falls within the clinical incubation period (~14-16 days) of COVID-19 cases (Dbouk & Drikakis, 2020; Lauer et al., 2020; Qin et al., 2020) reported by earlier studies.

3.4 Influence of the temperature and relative humidity on COVID spread over India

To understand the agreement and the influence of meteorological parameters on COVID spread between regional to spatial scale, we have extended our analysis for the entire India. Figures 10a and 10b depict the daily mean average surface temperature and relative humidity respectively during March 1 – December 5, 2020. It has been suggested that hot and dry regions of Indian territory are more susceptible to the COVID infection (Gupta et al., 2020; Sasikumar et al., 2020). However, we observed that the hot and high humid regions like Kerala, Tamil Nadu, Andhra Pradesh were severely affected by COVID spread when compared to hot and dry regions, which are mainly observed in the northwestern and central part of the Indian region (Figs 10a-b).

Figures 10c and 10d show the histogram of daily average surface temperature and relative humidity for the entire Indian states. It observed the temperature ranges from 12°C – 36°C and relative humidity ranges from 40-96 %. However, the maximum occurrence of the COVID-19 cases is falling between temperature ~26-30°C and relative humidity ~84-92%, respectively. Figure 10e shows the density plot of the daily COVID cases with the function of the temperature and relative humidity for overall Indian states. It is observed that COVID-19 cases have a tendency to increase with the decrease in the temperature and increase in the humidity; however, it does not have a perfect linear relationship. The COVID-19 cases with very low temperature (<20°C) and very high humidity (> 75%) are found to be rare. It appears that COVID-19 cases are favorable under the cold and semi-moist condition (temperature ~ 18-22°C and humidity 40-50%) as well as hot and humid (temperature ~24-32°C and humidity ~60-85%) conditions. These conditions are mainly associated with the transmission mechanism governed by evaporation rate and droplet size. As the evaporation is minimal at the temperature is lower (< 20°C), the semi-moist air acts as an optimal route for the long-range transport of the smaller particles, which leads to a higher risk of airborne transmission and vulnerable to the inhalation process. However, in dry and hot weather conditions, the evaporation rate is higher, which significantly reduces the viability of the virus (Dbouk &

Drikakis, 2020). Thus, we observe the dependency of the COVID-19 cases only for the intermediate values of the surface temperature and relative humidity (Auler et al., 2020; Ijaz et al., 1985; Ward et al., 2020).

Figure 10f shows the WTC analysis between daily COVID-19 cases and the surface temperature. The significant coherence between COVID-19 cases and the surface temperature is observed within 0-4 and 4-8-days frequency bands during mid-May, June, July, and mid-September.

During mid-May, June, July, and mid-September, we observed the significant positive coherence with 0-4 with surface temperature leading to the COVID-19 cases. In contrast, the first week of September shows negative coherence. Similarly, we observed the positive (negative) coherence during the last week of July (mid-August). In the early phase (March – mid June) of COVID-19 spread, most of the Indian states are prevailing with dry and hot weather; thus, its transmission was mainly controlled by the temperature fluctuations leading to the positive coherence. However, later during June – December, the inhomogeneous distribution of the relative humidity due to changes of the seasons from monsoon to winter results in a negative effect on airborne transmission, and hence we observed both positive and negative coherence. A similar phenomenon is also observed from WTC analysis between daily COVID-19 cases and relative humidity, as shown in Figure 10g. During (March – mid June) of COVID-19 spread was very slow, during which significant coherence was observed within 0-4 days frequency bands. Whereas, during June-December, the frequency of significant coherence is ~ 2-8 days. During mid-June, the first week of July, and mid-September, positive coherence is observed in contrast to mid-August, the last week of October and November.

Summary And Conclusion

The present study aims to understand the influence of surface temperature, relative humidity and rainfall on COVID-19 spread over five severely affected cities as well as the Indian continent. In this study, we employed a non-linear wavelet approach to study the influence of meteorological variables on COVID 19 spread instead of linear as most of the previous studies have demonstrated. Following conclusions and suggestions may be drawn from the present study.

1. From day-to-day variation of the COVID-19 cases, it is clearly observed that monsoon rainfall has played a key role in sustaining the spread to more or less at constant level over all the cities.
2. It is observed that both surface temperature and relative humidity was important factor in mobility of the COVID-19 cases. Over Delhi, Mumbai and Chennai, COVID-19 cases tend to increase with increasing temperature and decreasing humidity whereas over Kolkata and Bengaluru, COVID-19 cases tend to increase with decrease in surface temperature and increase in relative humidity. Over entire India, COVID-19 cases tend to increase with decrease in surface temperature and increase in relative humidity.
3. The highest number of COVID-19 cases are reported at warmer (24-30°C) and intermediate relative humidity (50–80%) indicating that COVID-19 infections are prone to the warmer and intermediate humidity conditions over the India region.

4. We observed that variability in the relative humidity was more critical than the temperature variability.
5. The time and frequency domain of the WTC analysis of the COVID-19 cases with the surface temperature and relative humidity have a significant coherence within 0–8 days.
6. After lifting the lockdown over India, COVID-19 cases suddenly started to increase to all cities especially over Chennai and Kolkata (where the cases increased by threefold within a short time) except Mumbai indicating that decision of unlocking would have been based on the localized COVID-19 cases instead of over COVID-19 cases.

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Declarations

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Declaration of interests

☐ 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.

CRediT author statement

Sanjay Kumar Mehta: Writing- Reviewing and Editing, Visualization, Investigation, **Aravindhavel A:** Data curation, Writing- Original draft preparation, conceptualization, Methodology, Software, Investigation **T. V. Ramesh Reddy:** Data curation, Software **Saleem Ali:** Data curation, Methodology, **Shyam Bihari Mehta:** Data curation.: **Sachin Philip:** Data curation: **Pooja Purushotham and K. B. Betsy:** Data curation.

Figures

Figure 1

Geographic locations of COVID-19 cases of selected severely affected Indian cities labeled in text.

Figure 2

Day-to-day variation of the (a) confirmed COVID-19 cases (b) temperature (solid orange line) (c) relative humidity (solid blue line) (d) rainfall over Delhi during 22 March (First lockdown start date) – 05 December 2020. The solid dashed line marks the lockdown (L1, L2, and L3; red) and unlocks (UL1-UL6; blue) periods. The month's end date is indicated as crossed. Daily COVID-19 cases (solid grey line) on a logarithmic scale are also superimposed on Figs 2b and 2c.

Figure 3

is the same as Figure 2 but plotted over Mumbai.

Figure 4

Same as Figure 2 but for Kolkata.

Figure 5

Same as Figure 2 but for Bengaluru.

Figure 6

Same as Figure 2 but for Chennai

Figure 7

The density plot of COVID-19 confirmed cases with the function of temperature and relative humidity observed over Delhi, Mumbai, Kolkata, Bengaluru, and Chennai (labeled in the text).

Figure 8

Wavelet transforms coherence (WTC) between COVID-19 cases with surface temperature over (a) Delhi, (b) Mumbai, (c) Kolkata, (d) Bengaluru, and (e) Chennai. The white curve represents the cone of influence. The right arrow ($\rightarrow$) and left arrow ($\leftarrow$) denote that temperature and COVID-19 cases are in phase (positively correlated) and out of phase (negatively correlated), respectively. Right-up or left-down arrows indicate the temperature is leading and left-up or right-down arrows COVID-19 cases are leading.

Figure 9

Same as Fig 8, but WTC analysis was performed between COVID cases and RH.

Figure 10

Influence of temperature (T) and relative humidity (RH) on COVID transmission over India during March to 5 Dec 2020. (a) Average T over Indian landmass (b) Average RH over Indian landmass (c) histogram of T (d) histogram of RH (e) density plot of daily average COVID cases with the function of T and RH (f) wavelet transform coherence (WTC) analysis between T with COVID (g) WTC analysis between RH with COVID daily cases.