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The nexus between COVID-19, temperature and exchange rate in Wuhan city: New findings from partial and multiple wavelet coherence

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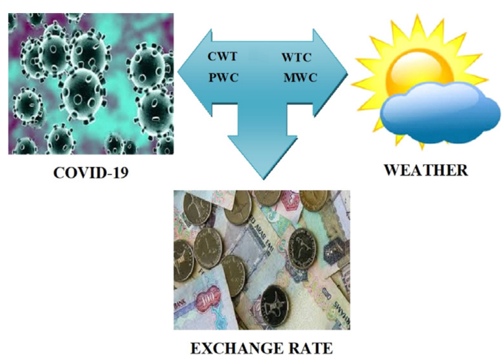
HIGHLIGHTS

- We have examined the covariance nexus between temperature, COVID-19 and exchange rate in Wuhan City, China.
- Novel methods of Wavelet Transform Coherence, Partial and Multiple Wavelet Coherence are employed for analysis.
- Temperature played no role in the containment of COVID-19 in Wuhan.
- COVID-19 outbreak in Wuhan had a negative but limited impact on RMB exchange rate against USD during our observation period.

GRAPHICAL ABSTRACT



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ABSTRACT

This study attempts to document the nexus between weather, COVID-19 outbreak in Wuhan and the Chinese economy. We used daily average temperature (hourly data), daily new confirmed cases of COVID-19 in Wuhan, and RMB (Chinese currency) exchange rate to represent the weather, COVID-19 outbreak and the Chinese economy, respectively. The methodology of Wavelet Transform Coherence (WTC), Partial Wavelet Coherence (PWC) and Multiple Wavelet Coherence (MWC) is employed to analyze the daily data collected from 21st January 2020 to 31st March 2020. The results have revealed a significant coherence between the series at different time-frequency combinations. The overall results suggest the insignificance of an increase in temperature to contain or slow down the new COVID-19 infections. The RMB exchange rate and the COVID-19 showed an out phase coherence at specific time-frequency spots suggesting a negative but limited impact of the COVID-19 outbreak in Wuhan on the Chinese export economy. Our results are contrary to many earlier studies which suggest a significant role of temperature in slowing down the COVID-19 spread. These results can have important policy implications for the containment of COVID-19 spread and macro-economic management with respect to changes in the weather.

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1. Introduction

The world is passing through an unprecedented situation as the novel corona-virus (COVID-19) is sweeping across the massive population of the world recently. The first case was reported in China's Wuhan during December 2019, and a statement from WHO (World Health Organization) confirmed the novel nature of the virus on 9th January 2020 (Zhu et al., 2020). Within the same month, WHO declared Public Health Emergency of International Concern (PHEIC) on 29th January 2020, citing concerns for the response capacity of the countries with weaker health systems (Sohrabi et al., 2020). Due to the highly contagious nature of COVID-19 ($R^0 = 2$-5, one patient can infect 2-5 others) and an ever-increasing number of cases in the other parts of the world, soon it became a pandemic (Liu et al., 2020a). The total number of confirmed cases and the deaths amount to a staggering 2,127,873 and 141,454 (04:33 hrs Beijing time, on 17th April 2020) respectively worldwide, according to the data from Johns Hopkins University, U.S.A. A recent study in Madrid, Spain suggests that COVID-19 may become more contagious along time, implying that R^0 may increase (Garcia-Iglesias and de Cos Juez, 2020). Its health impact is severe enough to put more than a half of the world's total population under some form of restriction, while the economic impact is being called worse than the 2008–09 Global Financial Crisis and being compared with the Great Depression of 1930. Stock markets around the world have seen the worst decline since decades (Baker et al., 2020). Researchers across the globe are struggling to document the nascent knowledge acquired through primary observation and experience of the situation. Efforts on a global scale are being made to know more about this virus and to slow down and ultimately stop the spread of this menace. Fig. 1 shows the daily number of new confirmed cases of COVID-19 in Wuhan from 21st January 2020 to 31st March 2020.

A sudden and huge increase in numbers on 13th February 2020 is due to the inclusion of a new criterion (Clinical Symptoms) for detecting confirmed COVID-19 cases. Fig. 2 shows map of the Chinese provinces with relative severity of the COVID-19 spread.

The COVID-19 virus belongs to the family of severe-acute-respiratory-syndrome (SARS) coronavirus and bears flu like symptoms. Since the weather is a key variable in predicting flu, hence it is likely to be an important factor for the COVID-19 too (Sajadi et al., 2020). Since severe cold, wind speed and rain (Weather variables) can contribute to flu, cold, fever, cough and pneumonia etc. all of which are the possible symptoms of COVID-19, it is imperative to know how the weather is associated with the new infections and transmission of COVID-19 in Wuhan, during this outbreak. Fig. 3 displays the daily average temperature (averaged from hourly observations) of Wuhan city from 21st January 2020 to 31st March 2020.

The outbreak of COVID-19 has severely restricted peoples' mobility and disturbed routine-life-activities of more than a half of the world's population. In this scenario, the negative economic impact of this disease on economy is imminent, especially in China where it was first reported and which is also amongst the worst affected (82,341infected and 3,352 dead till 17th April 2020) countries. As China is a production house of the world and a major portion of its Gross Domestic Product (GDP) depends on exports, the RMB exchange rate is expected to be disturbed too (Feng et al., 2016). Due to lockdown in Hubei (Central Chinese province of which Wuhan is the capital), the movement of people and goods to and from this place was completely halted. Due to the novel nature of COVID-19, it became difficult to ascertain if the virus could be spread through goods transport or not. In this uncertainty, other countries felt reluctant to allow Chinese made products to enter their borders. Production had already suffered due to complete lockdown in a whole province and then reduced demand overseas added further to the declining exports in China. All these factors can affect the value of Chinese currency, which is primarily linked to the foreign trade flows (Li et al., 2015). In such a scenario, it is interesting to know how the Chinese RMB exchange rate moved with the emerging situation of the COVID-19 outbreak, explicitly speaking the number of daily new confirmed cases in Wuhan during this period. Fig. 4 shows the trend of RMB exchange rate against USD on daily basis from 21st January 2020 to 31st March 2020.

This study attempts to document the relationship between local weather (Temperature in Wuhan), economy (Exchange rate of RMB), and COVID-19 outbreak (Daily number of new confirmed COVID-19 cases) in the Chinese city of Wuhan, using wavelet analysis. As it is an emerging situation, the research on different aspects of this global outbreak is still naive at the moment.

2. Literature review

Soon after reporting of the early cases of COVID-19, it was established that human-to-human transmission was taking place (Chen et al., 2020; Lai et al., 2020). Temperature is an important factor in infectivity reduction of the human corona-virus (Lamarre and Talbot, 1989). Previous experience with the SARS had demonstrated that the disease disappeared in warm weather during late July (Wallis and Nerlich, 2005). Similar behavior has been expected by some experts in the case of COVID-19 too, due to its relationship with the same family i.e., corona-virus (Wilder-Smith et al., 2020). Temperature and

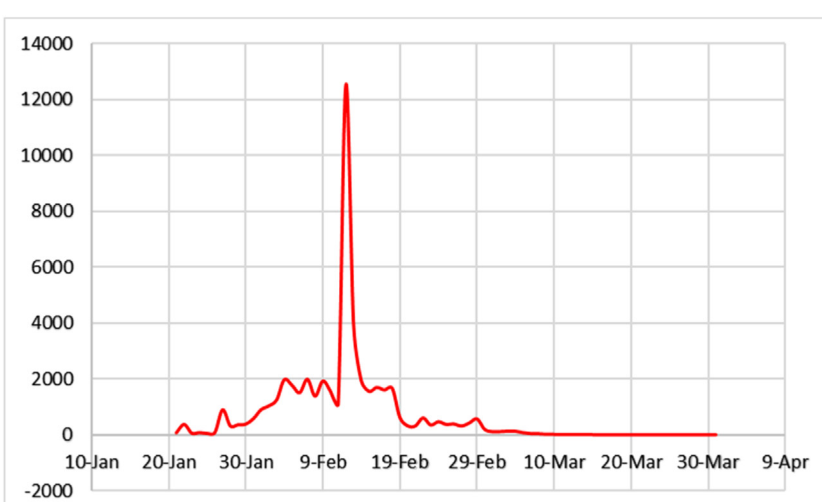

Fig. 1. COVID-19 daily new confirmed cases in Wuhan City.

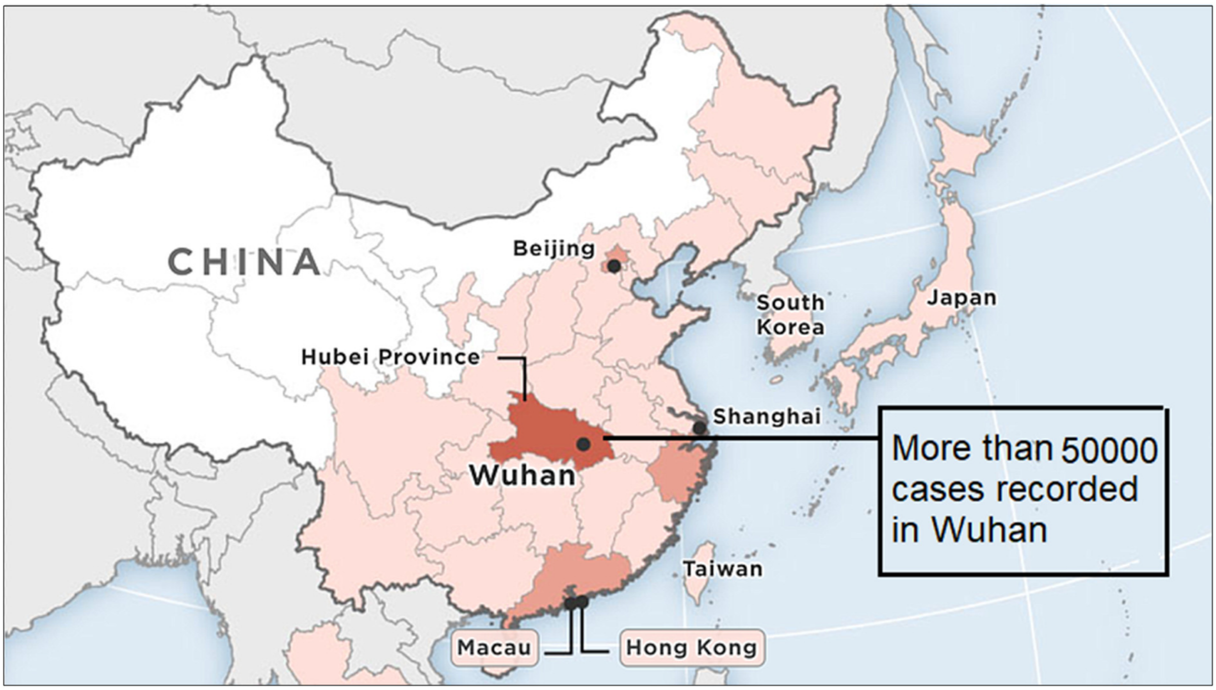

Fig. 2. Confirmed cases in Wuhan City.

humidity is an important factor in the survival of corona-virus on metal and other surfaces (Casanova et al., 2010). Higher humidity, lower temperature and tropical areas were found to be more feasible for the corona-virus spread during the SARS outbreak in 2003 (Chan et al., 2011). A recent study finds an association between meteorological factors, air pollutants and number of deaths in Wuhan due to COVID-19 outbreak, using the Generalized Additive Model (Ma et al., 2020). Weather is found to be associated with the daily number of new COVID-19 cases in the Indonesian capital city of Jakarta also (Tosepu et al., 2020). Research studies on the SARS outbreak of 2003 found that daily infections could increase up to 18 times at low temperatures as compared to high temperatures (Merlo et al., 2006). A study involving 429 cities around the world suggests that temperature may be an important factor in COVID-19 infection and transmission, and regions with similar weather conditions as of Wuhan should be extra cautious in preventing an outbreak (Wang et al., 2020). The same study suggests that there may be a best temperature for COVID-19 transmission and low temperature is more feasible for this infection and transmission. Another research, including data from all cities of China suggests that a rise in temperature leads to an increase in the doubling time of COVID-19 infections. This implies that high temperatures may reduce the speed of transmission of COVID-19. Although the model from this study explains only 18% of the variation in the doubling time of COVID-19 cases, it still provides an important insight into how the temperature can play a role in the containment of this outbreak (Oliveiros et al., 2020).

While the above mentioned studies suggest a decisive role of a rise in temperature in reducing COVID-19 transmission, the current spread around the southern hemisphere suggests there may be only little if any role of the temperature in this regard. According to a research on the global scale data, high temperature does not seem to slow down the COVID-19 spread (Jamil et al., 2020). Another study on community outbreaks throughout the world suggests that COVID-19 is a seasonal respiratory virus, spreading along the similar latitude (Sajadi et al.,

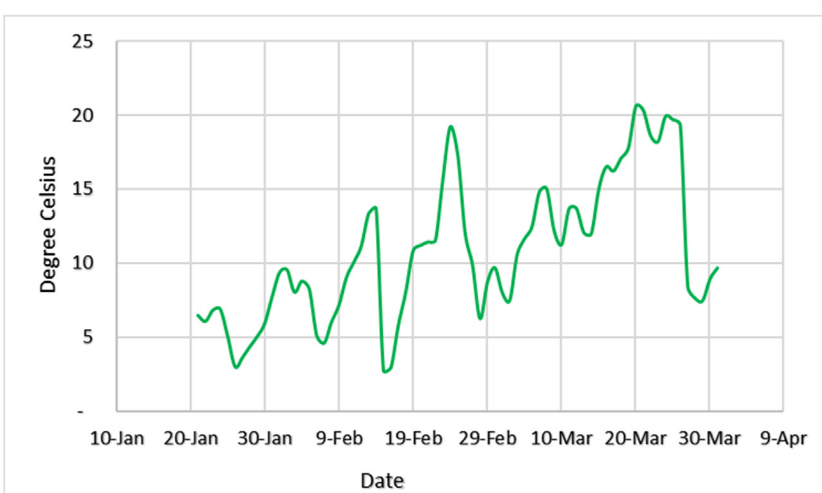

Fig. 3. Daily average temperature of Wuhan City.

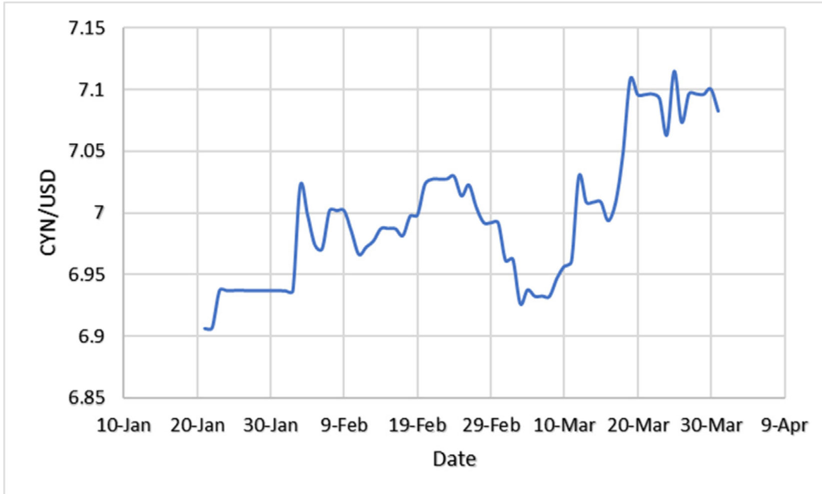

Fig. 4. Exchange rate CNY/USD.

2020). Below 3 degree centigrade, a rise in temperature is found to have increased the number of COVID-19 cases, according to a data analysis of 122 cities of China (Zhu and Xie, 2020).

In this uncertain situation where literature is inconclusive about the role of temperature in the COVID-19 spread, we attempt to analyze the coherence between daily new cases of COVID-19 and average daily temperature using the wavelet analysis. A better-modeled association helps to understand the behavior of this disease in varying weather conditions which can ultimately help to save more human lives by taking preventive measures. What has happened in Wuhan, is important for the rest of the world to know, to enable them to make informed and better decisions regarding COVID-19 containment. A recent study cited the measures taken in Wuhan as a model to contain the COVID-19 spread elsewhere in the world (Liu et al., 2020b).

A few studies confirmed the negative impact of the COVID-19 outbreak on the Chinese economy during its early stages (Al-Awadhi et al., 2020; McKibbin and Fernando, 2020). The Chinese economy is export-oriented, and any significant changes in exports due to COVID-19 can affect its exchange rate. A lot of research studies are available on the relationship between exchange rate and the exports of a country, especially in the case of China (Burdekin and Willett, 2019; Taylor, 2016). There is a positive relationship between the depreciation of RMB and the Chinese exports according to a number of those studies (Park et al., 2010) while others are inconclusive (Cheung et al., 2012). However, the current situation may be different as compared with the classical exchange-rate-exports relationship, due to its novel nature. In the ongoing scenario, the RMB exchange rate is expected to show some coherence with the COVID-19 outbreak, both directly and indirectly.

3. Data

Weather is represented by “average daily temperature” and calculated by taking 24 hourly observations in Wuhan on daily basis and then averaging throughout each day. COVID-19 outbreak is represented by the “number of daily new confirmed infections” of the COVID-19 and the numbers are taken from the National health commission of China's official website. Data on Chinese exchange rate against US dollar is taken from IMF (International Monetary Fund) website. All data values are included on daily basis from 21st January 2020 (2 days before lockdown start date of Wuhan city) to 31st March 2020.

4. Methodology

We have employed Continuous Wavelet Transform (CWT), Wavelet Transform Coherence (WTC), Partial Wavelet Coherence (PWC) and Multiple Wavelet Coherence (MWC) to analyze the association between the daily average temperature of Wuhan, daily number of new cases of COVID-19 in Wuhan city and the RMB exchange rate. The wavelet methodology is used mostly in Geophysics and recently getting footprints in weather, environment, economics, and finance related studies also (Afshan et al., 2018; Ng and Chan, 2012; Wu et al., 2019). It can capture non-linear associations between multiple series of data (Benhmad, 2012). Such a methodology has not been employed in any studies related to COVID-19, up to the best of our knowledge till now.

There are several advantages of using the wavelet approach in multiple time series analysis; 1) Assumption of stationarity can be relaxed. 2) A time series with non-normal distribution can be used. 3) Events localized in time can be captured efficiently. 4) Analysis is done from a time-frequency perspective. 5) It is very effective for capturing non-linear relationships (which is the case most frequently in the real world scenarios). 6) It can determine the strength and direction of the association and distinguish between short, medium and long term relationships at the same time. 7) Different types of wavelet functions can be used depending upon the nature of data which allows more efficient and accurate tracking of the co-movements. 8) It can capture bi-directional (lead-lag) relationships at the same time between different time-frequency combinations (Grinsted et al., 2004; Ng and Chan, 2012; Vacha and Barunik, 2012).

First, we transformed our data using "Morlet wavelet" for "continuous wavelet transform" and then employed WTC to check the co-movements. The mathematical equation for wavelet transforms coherence is presented below;

$$R^2(m,n) = \frac{\left|N(N^{-1}W_{xy}(m,n)\right|^2}{N(N^{-1}|W_x(m,n)|^2 N(N^{-1}} |W_y(m,n)|^2 \quad (1)$$

The WTC values range from $0 \le R^2(m,n) \le 1$.

Zero means no coherence at all and one means perfect coherence. The method of Monte Carlo simulation is employed for statistical significance. WTC is used to analyze the co-movement between two variables.

4.1. The Partial Wavelet Coherence (PWC)

In this methodology, the comovements are studied between two variables while controlling for the common effects of a third variable. The mathematical representation of PWC and WTC between different combinations of variables is given as under;

$$R(x_1,x_2) = \frac{S[W(x_1,x_2)]}{\sqrt{S[W(x_1)]S[W(x_2)]}}; \tag{2}$$

$$R^2(x_1,x_2) = R(x_1,x_2).R(x_1,x_2)*; \tag{3}$$

$$R(x_1,y) = \frac{S[W(x_1,y)]}{\sqrt{S[W(x_1)]S[W(y)]}}; \tag{4}$$

$$R^2(x_1,y) = R(x_1,y),(x_1,y)*; \tag{5}$$

$$R^2(x_2,y) = R(x_2,y),R(x_2,y)*; \tag{6}$$

$$RP^2(y,x_1x_2) = \frac{|R(yx_1)-R(y,x_2)-R(y,x_1)*|^2}{[1-R(y,x_2)]^2[1-R(x_2,x_1)]^2}; \tag{7}$$

Whereas "R" represents the coherence between two variables while "x_1", "x_2" and "y" represent the variables of interest. Eqs. (2–6) represent WTC between all three possible combinitions of variables x_1, x_2, and y. Eq. (7) shows the mathematical representation of PWC which calculates the WTC between variables y and x_1 while controlling for the common effects of x_2 on this relationship. The significance level in WTC, PWC and MWC is calculated using Monte Carlo method.

4.2. The Multiple Wavelet Coherence (MWC)

The simplest way of understanding the multiple wavelet coherence is to compare it with the coefficient of multiple correlation. In this method, a co-movement is studied between one dependent variable Y and the combination of two other (x_1 and x_2) independent variables. The mathematical representation of the MWC is shown below;

$$RM^2(y,x_2,x_1) = \frac{R^2(y,x_1)+R^2(y,x_2)-2\ Re[R(y,x_1).R(y,x_2)*.R(x_2,x_1)*]}{1-R^2(x_2,x_1)}; \tag{8}$$

Whereas "RM^2" represents the dependence of variable "y" on the linear combination of two other variables of interest, "x_1" and "x_2" respectively (Ng & Chan, 2012).

5. Results and discussions

Descriptive statistics show that average number of daily cases of COVID-19 are 704.31 in Table 1, ranging from a minimum of "0" to a maximum of 12,523 during our observation period. Average daily temperature is 10.7 degree Celsius, ranging from a minimum of 3 degree to a maximum of 21 degree centigrade. Exchange rate average is RMB 6.99 per USD, fluctuating between 6.90 and 7.11 which shows a limited variation (maximum 3%) during this period. Correlation between all three variables is positive and significant at the 1% level. Coefficient of correlation is 0.61 for COVID-19 and temperature, 0.56 for COVID-19 and exchange rate and 0.53 for temperature and exchange rate, respectively.

Fig. 5(a) shows the continuous wavelet transform of COVID-19 which reveals significant variations in the frequency domain of 0–4 and 4–8 periods during third week of observation. A very prominent and dark red circle inside the black lining, pointing to the phenomenon can be observed. The black cone-shape lining separating the bright colors inside from the light ones outside, is called "cone of influence" and represents essential "edge effects" along its borders.

Table 1
Summary statistics.

Variable	COVID-19	TEMP	EXCR
Mean	704.31	10.775	6.998
Std.Dev.	1607.467	4.802	0.056
Min	0	3	6.906
Max	12,523	21	7.115
Jarque-Bera	5048	8.610	5.385
P-value	0.000	0.013	0.087
Correlation Matrix			
COVID-19	1		
TEMP	0.611*	1	
	0.000		
EXCR	0.558*	0.532*	1
	0.000	0.000	

* Shows significance at the 0.01 level.

Fig. 5(b) shows the significant variations in temperature, prominent in frequency bands of 0–4, 4–8 and 8–16 during 3rd, 3rd-4th and 8th, and 3rd-6th weeks of observation respectively, represented by an "L" and a long oval shaped dark red contours.

Fig. 5(c) shows CWT of exchange rate, revealing small but significant variations in the frequency bands of 0–4, 4–8 and 8–16 during 2nd and 9th, and 2nd and 8th weeks respectively, represented by the small and scattered islands of red color.

The direction of clusters of small arrows observed in the Fig. 6(a), represents the direction of association between COVID-19 and temperature while the colored bar on the right side tells us the strength of this association. Arrows pointing towards right, mean a positive association (in phase) between these variables whereas negative (out phase) if pointed to the left. Arrows inside the circle (contour) mean a significant association. Rightward direction of arrows inside the contour represents positive association between temperature and COVID-19 in the frequency band of 8–16 periods, during third week of observation. Red color inside the circle matches with a correlation of almost 0.80 which is shown on the colored bar on the right side, representing a strong association. Black cone shape lining from top to bottom, on the both sides is called "cone of influence" and represents the significance level and essential edge effects along the borders.

Fig. 6(b) shows the small arrows pointing towards left, inside the circle and prominent on the base with red color inside. This means a negative association (out phase coherence) between COVID-19 and exchange rate in the frequency band of 16 to onwards during 4th and 5th weeks of observation. Dark red color inside is the contour is matching with an association (coherence value) of more than 0.90 as represented by the colored bar on the right side, showing a very strong impact of COVID-19 on exchange rate here. Important edge effects are also observable in the same frequency region prior to 4th week. The WTC can be thought of as a correlation that is localized in time-frequency domain in simple terms but possesses many advantages over a simple correlation measure (Grinsted et al., 2004).

Temperature and exchange rate are in phase as shown by the arrows pointing towards right in the circle shown on the base of the Fig. 6 (c) and inside the cone of influence. Red color inside is equal to almost 0.80, shown on the colored bar on the right which means a strong association in the frequency range of 16 and onwards during 4th and 5th weeks of observation. There are notable edge effects also in the same frequency band before and after 4th and 5th week. There is another very small cluster of arrows pointing towards left, in the frequency range of 0–4 bands during 2nd week which implies an out-phase association between exchange rate and temperature. Overall, it's a mixed trend in association between these two variables.

Fig. 7a-1 shows result of Partial Wavelet Coherence (PWC) involving COVID-19, temperature and exchange rate. It shows the wavelet coherence between COVID-19 and temperature while controlling for exchange rate effects. One small and the other large and red colored contour can be observed in the frequency bands of 0–4 and 8–16

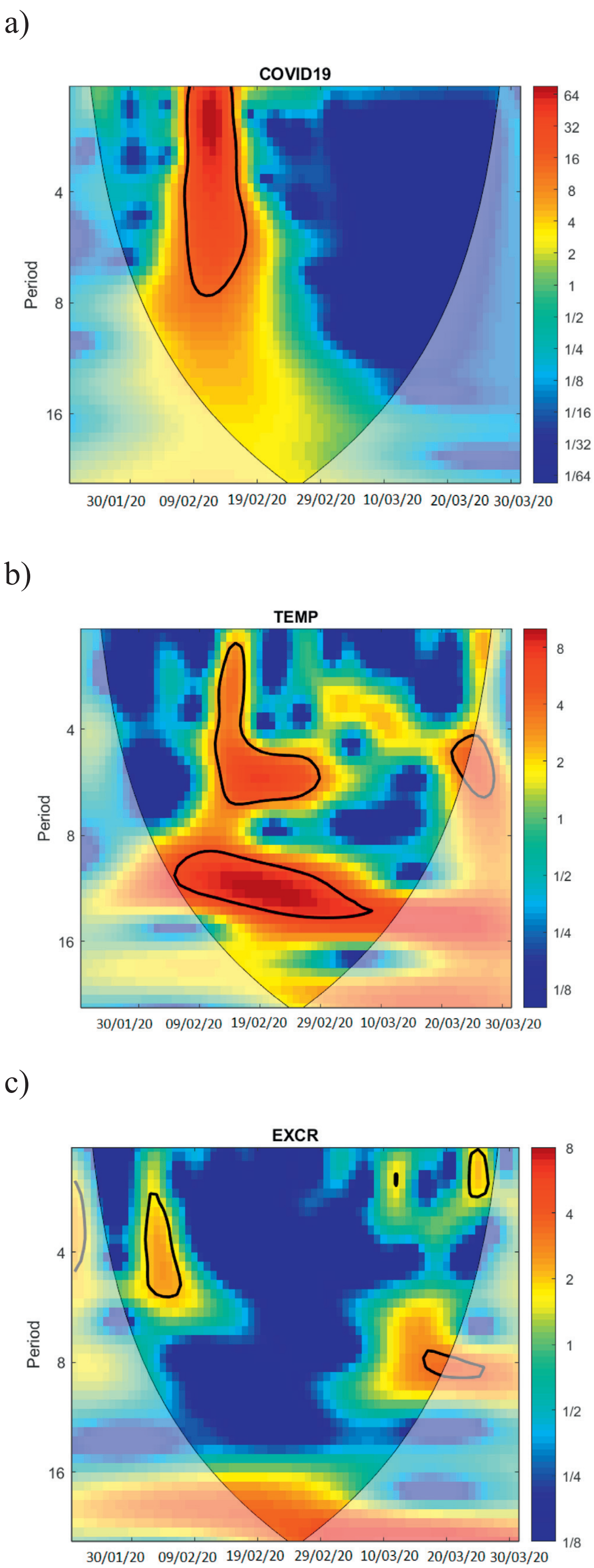

Fig. 5. Continuous wavelet transform of COVID-19, TEMP and EXCR.

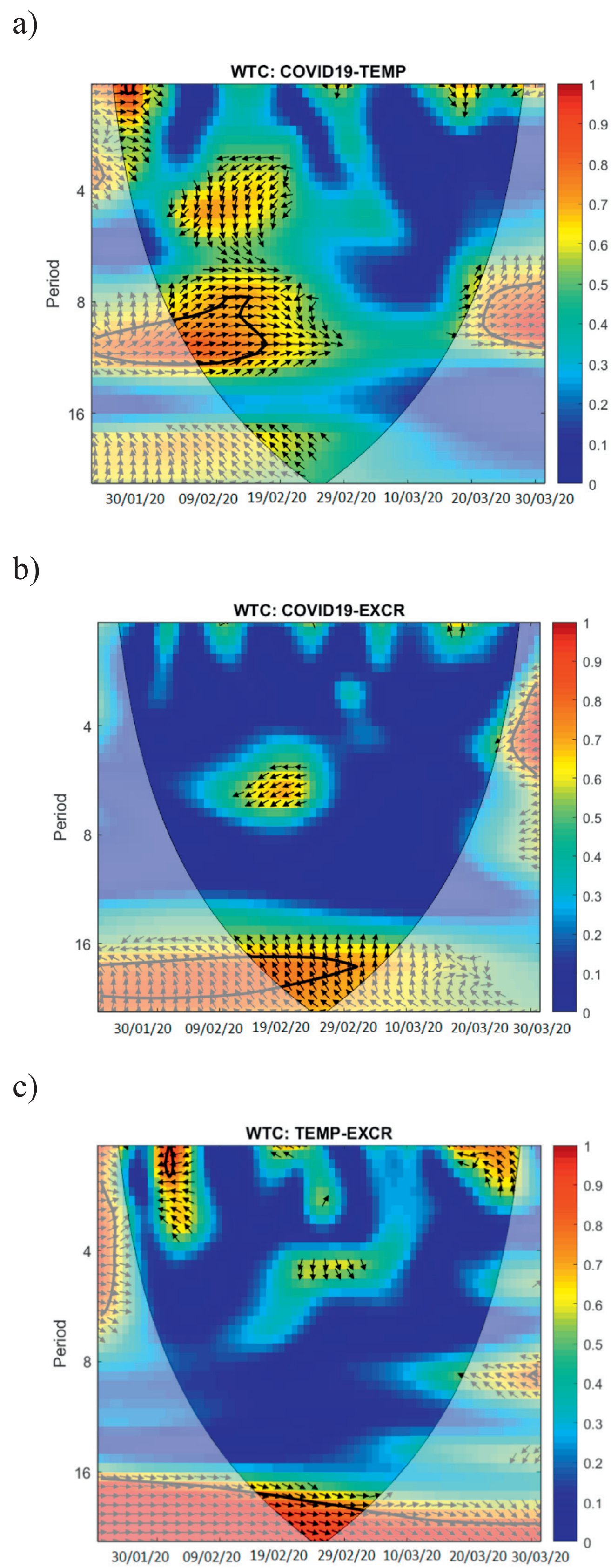

Fig. 6. Wavelet transform coherence of COVID-19, TEMP and EXCR.

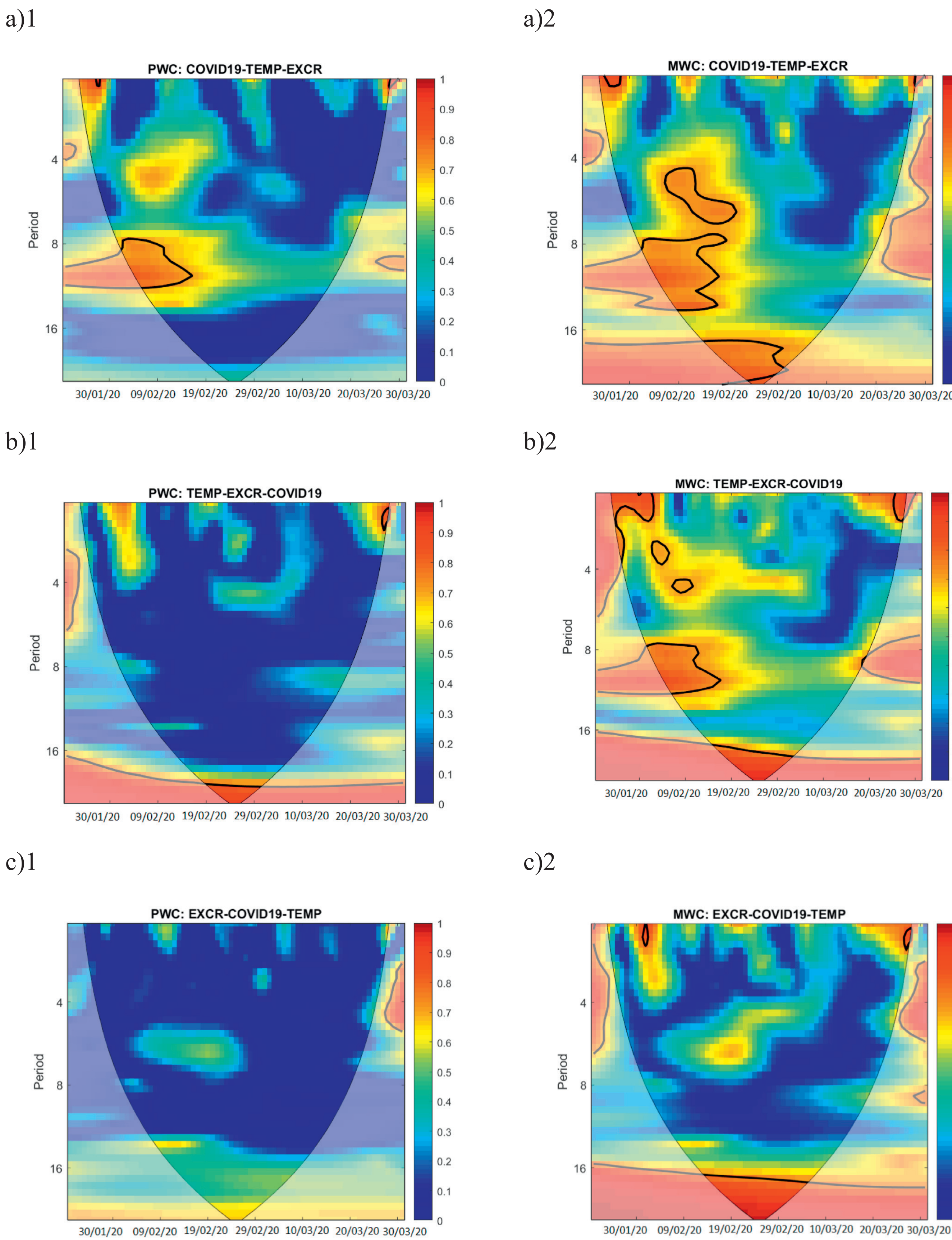

Fig. 7. Partial and multiple wavelet coherence of COVID-19, TEMP and EXCR.

periods respectively, showing both short and long term coherence within the given time period. Short term coherence is observed during 1st week while long term between 2nd and 3rd week of the observation. Red color inside the contour is almost equal to 0.80 as shown on the vertical colored bar, representing a strong association. If we compare this result with WTC result of COVID-19 and temperature from Fig. 6a, the both are almost same. This implies that exchange rate has no significant impact on the relationship between COVID-19 and temperature and results of WTC show the true coherence between COVID-19 and temperature.

Fig. 7b-1 shows the PWC result involving temperature, exchange rate and COVID-19. Specifically, it shows the WTC between temperature and exchange rate after controlling the common effects of COVID-19. The only notable difference here from Fig. 5b is an additional small contour, in the frequency band of 0–4 during the last week of observation which is absent in the case of results from WTC.

Fig. 7c-1 shows the PWC result involving exchange rate, COVID-19 and temperature. After controlling the common effects of temperature, there seems little coherence between exchange rate and COVID-19 as evident from the large blue areas inside the figure. On the other hand, results from Fig. 6b show an out phase (negative) association between COVID-19 and exchange rate. This situation involving PWC and WTC result shows a significant impact of temperature on the relationship between exchange rate and COVID-19.

The MWC shows how good the linear combination of independent variables co-moves with a dependent variable. Fig. 7a-2 presents the result of MWC, involving COVID-19 as dependent while temperature and exchange rate as the independent variables. The linear combination of both independent variables explains the variations (Small and large red circles with black outlining) in COVID-19, in almost all frequency bands including 0–4, 4–8, 8–16 and 16 to onwards during 1st, 3rd-4th, 2nd-3rd and 4th–5th weeks of observation respectively.

Fig. 7b-2 shows the MWC result of temperature as dependent while exchange rate and COVID-19 as independent variables. Here also, red colored islands with black outlines can be observed in all the frequency bands, including 0–4, 4–8, 8–16 and onwards during 1st-2nd and 9th, 3rd, 3rd-4th and 5th week of observation respectively. These small and large, red colored contours show the strength of the combination of exchange rate and COVID-19 in predicting temperature. The more the red color, the more the variation can be explained in temperature by the combination of exchange rate and COVID-19.

Fig. 7c-2 shows the MWC result, involving exchange rate as dependent while temperature and -19 as independent variables. Two small circles can be observed in the frequency band of 0–4 during 2nd and last weeks of observation respectively, while a large red circle in the frequency band of 16 and above during 4th and 5th week of observation. These red areas show the association between exchange rate and a linear combination of temperature and COVID-19 in that particular time-frequency space.

6. Conclusion

Average daily temperature of Wuhan shows a positive (in phase) coherence with the daily number of new COVID-19 cases, in medium term considering the given observation period. Similar results obtained from WTC and PWC add to the robustness of this outcome. It suggests that increase in temperature did not play any significant role in containing the COVID-19 spread in Wuhan. This result is contrary to a lot of other studies, suggesting that a rise in temperature may help to stop the COVID-19 spread. Our results are applicable for a temperature range between 3 degree and 21 degree centigrade which is the minimum and maximum temperature observed during the observation period. Although exchange rate and COVID-19 showed a significant negative (out phase) coherence for a short period of time, during 4th and 5th weeks of observation, the impact of COVID-19 on RMB exchange rate is not very large. The MWC results negate any huge, combined impact of COVID-19 and temperature on RMB exchange rate, suggesting a little impact on the Chinese exports during our observation period. Overall results show a significant co movement and coherence between COVID-19, exchange rate and weather in Wuhan.

Although wavelet analysis is relatively new and better approach as compared with correlation and many other time series techniques, from many aspects as stated above in the methodology section, the results from this approach still need a caution in interpretation when talking about causality. In the absence of any sound economic/scientific/social theory, there may not be any causation and the data may show mere correlations and co-movements.

CRediT authorship contribution statement

Najaf Iqbal: Writing - original draft, Supervision, Writing - review & editing.**Zeeshan Fareed:**Formal analysis, Writing - original draft. **Farrukh Shahzad:**Conceptualization, Data curation, Formal analysis, Methodology.**Xin He:**Writing - original draft.**Umer Shahzad:**Writing - original draft.**Ma Lina:**Writing - original draft.

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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