Spatiotemporal distribution and trend of COVID-19 in the Yangtze River Delta region of the People's Republic of China

Lei Ye[1] and Lingqian Hu[2]

[1]School of Geographic Science, Nantong University, 999 Tongjing Ave, Nantong, Jiangsu, People's Republic of China; [2]School of Architecture and Urban Planning, University of Wisconsin-Milwaukee, Milwaukee, WI, USA

Abstract

An outbreak of atypical pneumonia, now called COVID-19 and known to be caused by the novel coronavirus SARS-CoV-2, first detected in Wuhan, Hubei Province of the People's Republic of China in December 2019 and afterwards rapidly spread worldwide. Wuhan and the Yangtze River Delta (YRD) region implemented first-level public health emergency responses to stop the spread of the virus on January 23rd, 2020. We tracked the geographical gravity centre of the disease and calculated spatial autocorrelation to explore the spatiotemporal patterns of distribution of imported and locally disseminated COVID-19 cases under the emergency-response control measure. We also applied polynomial regression analysis to estimate the trend of the COVID-19 in the YRD region before and after the control activities against the spread of the infection were instituted. The results show that the control measures applied have been effective. And, in the YRD region, areas with a large influx of population flow from Wuhan and Hubei Province had high risks of COVID-19. Therefore, identification of the spatiotemporal trends should be the first step when developing effective policies to manage and control any new epidemic. The results are not only informative locally but also useful for the rest of the world.

Correspondence: Lingqian Hu, School of Architecture and Urban Planning, University of Wisconsin-Milwaukee, Milwaukee, P.O. Box 413, WI, USA
E-mail: hul@uwm.edu

Key words: COVID-19; pandemic; China; geographic analysis; gravity center; spatial autocorrelation; polynomial regression.

Conflicts interests: the author declares no potential conflict of interest.

Funding: Lei Ye's work was supported by Natural Science Foundation of Jiangsu Province (Young Scholar Project) (BK20170440).

Received for publication: 11 April 2020.
Accepted for publication: 30 April 2020.

Geospatial Health 2020; 15:889
doi:10.4081/gh.2020.889

Introduction

Emerging and reemerging pathogens constitute a global challenge for public health (Gao, 2018). Given their high prevalence and wide distribution, novel coronaviruses are likely to emerge at various intervals (Cui *et al.*, 2019). The recent threat of the novel coronavirus SARS-CoV-2, the cause of the disease COVID-19, was first noted in late December 2019 in Wuhan, the capital of Hubei Province, the People's Republic of China (Zhou *et al.*, 2020). In January 2020, the virus spread to other parts of Hubei Province and then to other Chinese provinces. On January 23rd 2020, two days before the Chinese New Year, Wuhan was locked down and enforced a first-level public health emergency response that included banning travel from/to other cities, closing all non-essential public places, and executing a "stay-at-home" order. On the same day, the Yangtze River Delta (YRD) region implemented similar control measures, and within the next few days, most provinces/municipalities in mainland China were also locked down. As COVID-19 spreads rapidly in time and broadly across space, it is important to delineate its temporal and spatial distribution trends and find effective measures for local prevention and control.

The YRD region played an important role in the further spread of the new coronavirus as it has high population mobility and strong international ties based on being one of the six largest urban agglomerations in the world (National Development and Reform Commission, 2010). In the context of the current global COVID-19 outbreak, the YRD region is a good case study for examining the spatiotemporal dissemination patterns, especially for regions with high inter-city, inter-regional, and international connections. These regions are challenged by both imported cases and local dissemination. The management and control experience in the YRD region can be used as a reference for other mega-urbanized regions in the world.

This study was initiated to i) explore the spatiotemporal patterns of the COVID-19 dissemination; and ii) estimate its temporal trend in the YRD. We examine the daily number of new cases in the region to describe the spatial spread of the virus spread, apply spatial autocorrelation to find irregularities in COVID-19 distribution, and estimate polynomial regression analysis to describe the temporal trend under the strict control measures.

Literature review

Existing studies of infections mainly deal with pathogenesis, diagnostics and treatment, pandemics surveillance, prevention, control strategies research and development of drugs and vaccines (Ross *et al.*, 1976; Chowell *et al.*, 2003; Oparil *et al.*, 2003; Ecker *et al.*, 2005; Ginsberg *et al.*, 2007; Hilgenfeld *et al.*, 2013; Di *et* al., 2013; Wong *et al.*, 2015), with few papers examining spatiotemporal patterns of the spread of infectious agents. Identifying geographical differences in disease prevalence and understanding the spread of diseases over time are crucial starting points for epidemiology as noted by Doll (2008) early on. As spatiotemporal analysis results can be instrumental in developing regional or local prevention and control measures, it is important to conduct such analyses also in the fight against COVID-19.

Spatial analysis is crucial when investigating the spread of infections. Already, in 1854, John Snow drew a map of London's Soho district, revealing that cholera was caused by water pollution and not airborne as was previously speculated (Brody *et al.*, 2000). With the progress of science and technology, Geographic Information Systems (GIS) have emerged, proving a new tool for understanding effective control of the distribution of infectious diseases, e.g., for the identification of spatiotemporal patterns of pandemics to inform response measures against these pandemics (Comber *et al.,* 2001; Reinhardt *et al.,* 2008). Sanson *et al.* (1991) used GIS to improve the control management of the foot-and-mouth disease in New Zealand in 1991, while Gibbens *et al.* (2002) showed how the foot-and-mouth disease had spread throughout the country. In 2003, the National SARS Pandemics Control and Early Warning Geographic Information System developed by the Chinese National Center for Disease Control and Prevention (China CDC) played an important role in managing, analyzing and controlling the then new Severe Acute Respiratory Syndrome (SARS) (Liang *et al.*, 2004). More recently, Forna *et al.* (2020) detected spatiotemporal heterogeneity of the Case Fatality Rate (CFR) of Ebola in West Africa.

Despite the short time since its emergence, many studies on COVID-19 have already been published, most of them focusing on the evolution of the virus and its health impacts. In January 2020, Zhu *et al.* (2020) announced the outbreak of pneumonia of an unknown cause in Wuhan, China, while Wu *et al.* (2020) soon after estimated the number of cases based on the number of cases exported and also assessed the extent of domestic and global public health risks. Backer *et. al*. (2020) estimated the average incubation period of COVID-19 by using reported travel histories and the dates that patients showed symptoms. Gu *et al.* (2020), using polynomial regression analysis, inferred that the inflection point of COVID-19 may have been passed by March 2020.

Generally, COVID-19 cases are distributed unevenly, and possible reasons include spatial proximity, city size, and environmental factors (Rivas *et al.*, 2020; Kamel *et al.*, 2020; Poirier *et al.*, 2020). In January 2020, examining the spatiotemporal characteristics of COVID-19 cases, Miao *et al.* (2020) at the Collaborative Innovation Center of Yellow River Civilization pointed out that the three cities, Xinyang, Zhumadian, and Nanyang, in Henan Province closest to Wuhan had the highest risk. Liu *et al.* (2020) suggested that medium-sized cities may have higher COVID-19 risks than large or small cities since large cities have abundant health services and small cities have limited population flow, while medium-size cites are caught in the middle. Liu *et al.* (2020) estimated that at least 51.3% of the population who left Wuhan to nearby prefecture-level cities traveled to rural areas, suggesting that control and prevention of COVID-19 should also pay attention to those areas. Although studies on the COVID-19 have added to our knowledge of this disease, few studies have examined the spatiotemporal distribution of COVID-19 cases. The limited number of studies do not provide sufficient information. First, they rely on data within a short period of time, which is expected as early studies have insufficient time to collect data. Second, existing studies tend to use large geographic units, such as prefectural cities for the study of intra-city spatial variation. Findings based on such large units might lack spatial accuracy and thus have limited policy implications for spatially targeted control measures.

Materials and Methods

Data source

The number and location of COVID-19 cases from January 20th to March 10th, 2020 were collected from the China CDC. The data cover all prefectural cities, including its counties and urban districts, in the YRD region (Figure 1). By the end of our study period, March 10th, COVID-19 appeared to be under control in the YRD as most counties/districts had no new cases for at least one week. We extracted the dates of confirmation for all cases, separated them into imported cases with a history of living/traveling in Hubei Province and locally disseminated cases without such a history.

Study area

Based on the "Regional Development Plan of the Yangtze River Delta" issued by the State Council in June 2010, the YRD region contains three sub-regions: Shanghai Municipality, Jiangsu Province, and Zhejiang Province. In addition to Shanghai, there are 24 prefecture-level cities and 133 counties/districts in the YRD region. The counties/districts are the spatial base unit of the analysis (Figure 1).

The study area is roughly grouped into eight areas with

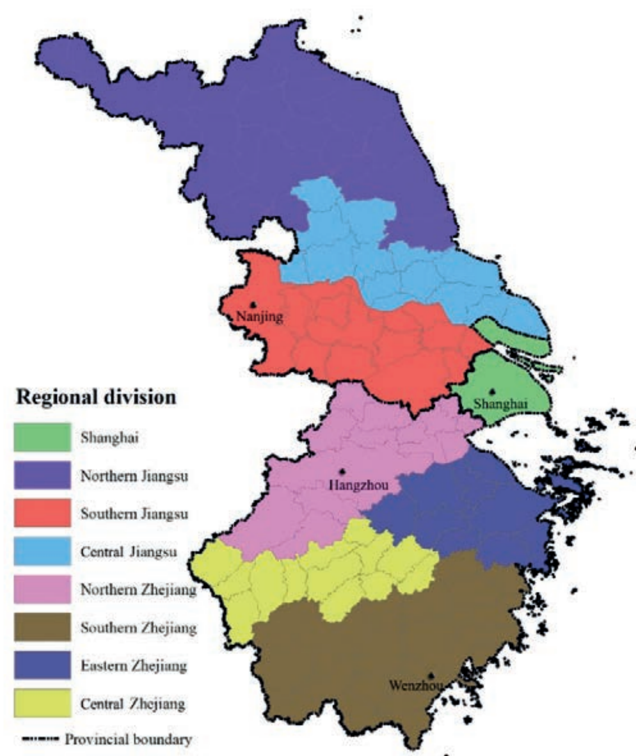


Figure. 1 Study area.

Shanghai as the core city. The province of Jiangsu is separated into three areas: northern, central, and southern Jiangsu. The latter includes the city of Nanjing, the provincial capital. Similarly, the province of Zhejiang is separated into four areas: northern, central, southern, and eastern Zhejiang. Northern Zhejiang includes the city of Hangzhou, the provincial capital. Southern Zhejiang includes the city of Wenzhou, which is famous for its business entrepreneurship; importantly, many Wenzhou business persons work in Hubei province, and both Hangzhou and Wenzhou have a lot of economic connections with Wuhan and Hubei Province as a whole. According to data from the National Bureau of Statistics of China, the YRD region covers an area of 210,700 km^2, 2.2% of the total area of the country. In 2019, the region had a total population of 160 million and a total GDP of USD 2.86 trillion, accounting for 11.4% and 20.0% of the Chinese total, respectively (National Development and Reform Commission, 2010). We chose the YRD region as the study area due to its economic conditions and its high connectivity with other regions. The total GDP of the YRD region is similar to that of the United Kingdom (USD 2.83 trillion), France (USD 2.71 trillion), Italy (USD 2 trillion), and California (USD 3.1 trillion) (National Bureau of Statistics of China, 2020). Like these European countries and American states, the YRD has a very high inter-city/regional/national connectivity and can therefore be seen as a template.

Spatial Statistical Analysis

We imported the collected COVID-19 case data into ESRI shapefiles (ESRI, Redlands, CA, USA) and used these shapefiles for the following spatiotemporal analyses:

Geographic centre

The first method to describe the temporal and spatial dynamics of COVID-19 distribution is to calculate the gravity center of daily new cases according to Chen (2015) using the following formula:

$$\overline{X_t} = \frac{\sum_{i=1}^{n} X_i Z_{it}}{\sum_{i=1}^{n} Z_{it}} \quad \overline{Y_t} = \frac{\sum_{i=1}^{n} Y_i Z_{it}}{\sum_{i=1}^{n} Z_{it}} \qquad \text{(Eq.1)}$$

where X_t and Y_t are the geographical abscissa and ordinate of newly added cases on the date t with i denoting county/district i and n the total number of counties/districts (n=133). X_i and Y_i are the longitude and latitude of county/district i and Z_{it} the number of newly added cases in county/district i on the date t.

Spatial autocorrelation

To analyze the spatial correlation in the distribution of COVID-19 cases, we used global and local Moran's I statistics (Basu *et al.,* 1998). The expression of the global Moran's I statistic is:

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} * \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(m_i - \overline{m})(m_j - \overline{m})}{\sum_{i=1}^{n}(m_i - \overline{m})^2} \qquad \text{(Eq.2)}$$

$$Z = \frac{I - E(I)}{\sqrt{VAR(I)}} \qquad \text{(Eq.3)}$$

where m_i represents the number of cumulative confirmed cases in county/district i; $\overline{m}$ the average number of cumulative confirmed cases in all 133 counties/districts, and w_{ij} the weight matrix.

For Moran's I, the standardized statistic Z can be used to decide whether the spatial autocorrelation is statistically significant or not. $E(I)$ and $VAR(I)$ are the theoretical mean and variance of Moran's I scores. If Z is between -1.96 and 1.96, the spatial correlation in the number of cases is not significant at the p=0.05 level. However, when the absolute value of Z is greater than 1.96, there is a statistically significant spatial correlation.

Calculation of the local Moran's I statistics is done by the following formula:

$$I_l = \frac{n(m_i - \overline{m})\sum_{j=1}^{n} W_{ij}(m_j - \overline{m})}{\sum_{i=1}^{n}(m_i - \overline{m})^2} \qquad \text{(Eq.4)}$$

where I_l is the local Moran's I score of county/district l. All the other notations are the same as in the previous equations. I_l can indicate four situations: i) a high case number of county/district l is associated with high numbers in the surrounding counties/districts (High-High); ii) a low case number of county/district l is associated with low numbers in the surrounding counties/districts (Low-Low); iii) a high number of cases in county/district l is associated with low numbers in the surrounding counties/districts (High-Low); and iv) a low number of cases in county/district l is associated with high numbers in the surrounding counties/districts (Low-High). The first two situations are expected, and the last two situations denote spatial irregularities that need further examination.

Polynomial Regression

Polynomial regression analysis, between a dependent variable and a series of *k-th* degrees of one or more independent variables (Max *et al.*, 1976), is appropriate in predicting the trend of development. Gu *et al.* (2020) showed that polynomial regressions, including quadratic, cubic, quartic, or exponential functions, can satisfyingly estimate the temporal trends of daily confirmed cases. The unary *k-th* degrees polynomial regression equation is as follows:

$$y_x = b_0 + b_1 x + b_2 x^2 + \ldots + b_k x^k \qquad \text{(Eq.5)}$$

where y_x is the number of newly added cases on day x, while b_0 b_1, $b_2 \ldots b_k$ are constant terms and x the number of days in the study period.

Results

The results show that the control measures are generally effective: the number of imported cases declined one week after the lockdown of Wuhan, and the number of locally disseminated cases declined after another week. The few areas with the highest number of COVID-19 cases are those with a large influx of population from Wuhan or other parts of Hubei Province.

The number of COVID-19 cases

The number of new COVID-19 cases in the YRD region passed its peak at the time of completing this study on March 10th. The daily new cases in Shanghai, Jiangsu Province, and Zhejiang Province rapidly declined and stayed at zero after March 3rd, indicating that the control measures in this region had achieved plausible results.

Figure 2 shows changes in the total number of cases and in the number of daily new cases in the YRD region between January 20th and March 10th, 2020. The daily new cases in the YRD region peaked on January 29th (183 cases) and decreased afterwards, except lower rebounds on February 3rd and February 20th. The number of new cases since February 21th was fewer than 10 per day.

Figure 3 displays the numbers of imported and locally disseminated cases per million resident population in the YRD region. The trend is similar to that observed in Figure 2. Figure 3 shows that Zhejiang generally had a higher number of cases (including imported and disseminated) than Shanghai and Jiangsu. The number of cases per million population was below 0.8 in Shanghai and Jiangsu, while the number in Zhejiang nearly doubled that during most of the study period. In addition, the number of imported cases in the whole YRD region had been zero or close to zero since February 15th, and the number of disseminated cases had begun to converge to zero with a few small rebounds. The plausible results reflect the effectiveness of strict and swift control measures in the YRD.

The temporal changes displayed in Figure 3 also illustrate the time it takes for the control measures to take effect. The rapid spread of COVID-19 was curbed within four weeks after the control measures were instituted in Wuhan and the YRD on January 23rd. Specifically, after Wuhan was locked down, it took about 7 days (to January 30th) to reach the peak of imported cases in the YRD. Local dissemination of COVID-19 continued, though. In another week, the number of locally disseminated cases reached its peak and then declined in Shanghai and Zhejiang. Jiangsu did not show a noticeable peak in the number of disseminated cases. In a total of four weeks, the imported and disseminated cases were under control in the YRD.

Spatial distribution of COVID-19 cases

Spatial analysis shows that the places with the highest risk are those with high population inflow from Wuhan and Hubei Province. Figures 4 a-c show the distribution of COVID-19 cases by March 10th in the YRD. Figure 4a displays the total number of confirmed cases. The counties/districts with high concentrations of confirmed cases are in Shanghai, southern Jiangsu, northern and southern Zhejiang, which have good railway connections to Wuhan and other cities in Hubei Province.

Figure 4b shows the spatial distribution of imported cases. In addition to Shanghai, which is expected to have many imported cases as the hub for population flows, some counties/districts in northern and southern Zhejiang also showed high numbers of imported cases greater than 30, suggesting that these areas suffered from the inflow of people carrying the virus. We speculate the reason is that a large number of business persons from Wenzhou, the centre of southern Zhejiang, own and do business in Hubei, and they returned to Wenzhou carrying the virus, during the Chinese New Year holiday (Kai, 2020). As a result, Hangzhou, the provincial capital and transportation hub of Zhejiang Province, was also affected by the inflow of travelers from Hubei who needed to make transfers to go to other cities in Zhejiang.

Figure 4c shows the number of locally disseminated cases. As expected, Shanghai, Northern Zhejiang, and Southern Zhejiang, with high numbers of imported cases, also had high numbers of locally disseminated cases. Meanwhile, some counties/districts in southern Jiangsu, including the provincial capital of Nanjing, had relatively large numbers of disseminated cases although

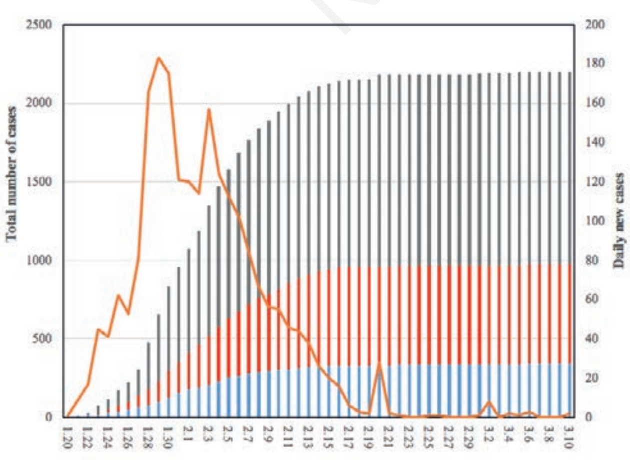


Figure 2. Changes in the total number of cases and daily new cases in the YRD region.

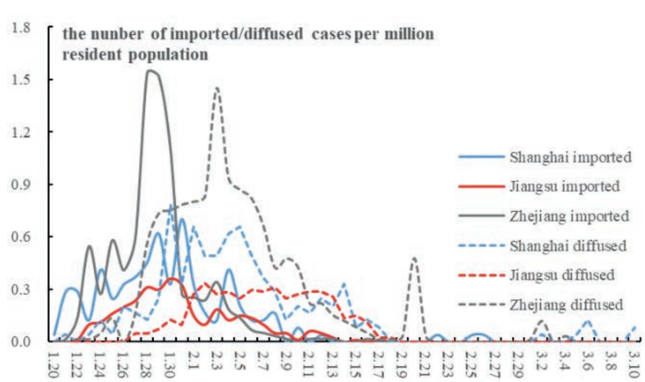


Figure 3. The number of imported and disseminated cases per million resident population in the YRD region.

without high numbers of imported cases, suggesting uncertain local risks even when the imported cases are few.

Figure 5 shows the change in the geographical center of gravity of the daily new cases, estimated based on Equation 1. The centre of daily new cases was initially in the southern part of the YRD, that is, Central Zhejiang, the places that suffered from imported cases in the first 20 days of February, the gravity center gradually shifted northwest. During that time, an increasing number of new cases started to emerge in Jiangsu while the number declined in Zhejiang. The analysis based on Figures 3 and 4 suggests that some places in Jiangsu had a relatively greater number of disseminated cases, which occurred after the waves of imported cases. However, since February 20th, the number of daily new cases in the YRD had been very few, and thus the geographical gravity center was significantly affected by the sporadic locations of new cases. Since then, no specific spatiotemporal clusters of new cases can be detected.

Spatial autocorrelation analysis of COVID-19 cases

COVID-19 cases have a high spatial autocorrelation. Based on the total number of cases, we calculated the global *Moran's I* and Z Scores, which equal 0.14 and 2.33, respectively. In other words,

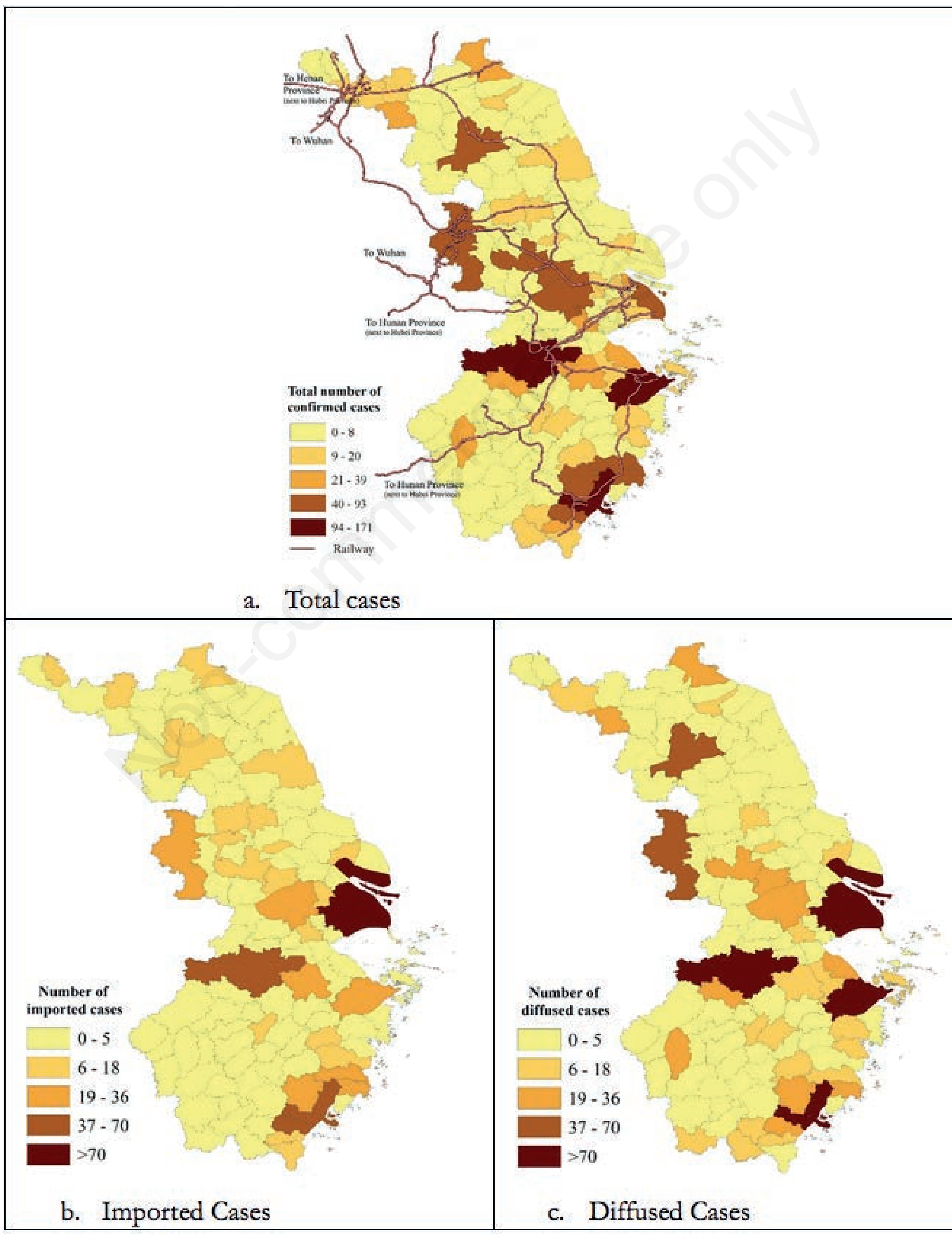


Figure 4. Distribution of COVID-19 cases.

the total number of COVID-19 cases in the YRD had an expected spatial correlation: the numbers of cases in proximate countries/districts are positively correlated.

Figure 6 shows local spatial correlation scores: I_l based on equation 4. The scores indicate whether the numbers of cases in individual counties/districts correlate with the numbers in surrounding counties/districts. Eight countries/districts have statistically significant local spatial correlation scores, including six counties in a high-high cluster (the red cluster of Wenzhou), one county as a low-high outlier (light green district of Yuhuan County in the red cluster of Wenzhou), and one as a high-low outlier (the blue outlier of Hangzhou). The observations suggest spatial irregularities in COVID-19 distribution that require further exploration.

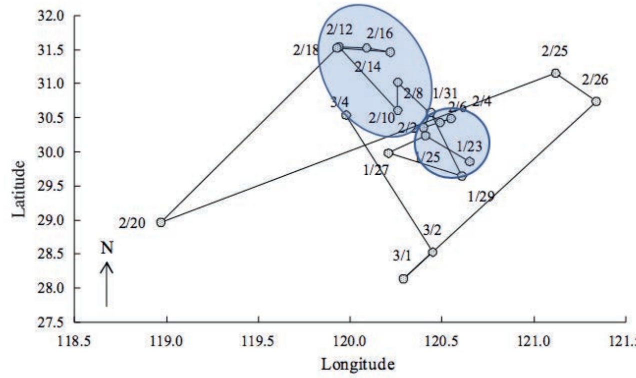
The high-high cluster includes counties/districts in and surrounding Wenzhou, which is unique with a high number of business persons who operate or own businesses in Wuhan. Based on the data from Wuhan-Wenzhou Chamber of Commerce, 180,000 Wenzhou business persons work in Wuhan, and about 20,000 of them returned to Wenzhou during the Chinese New Year holiday (Wuhan-Wenzhou Chamber of Commerce, 2020). Additionally, a large number of migrant workers from Hubei Province work in Wenzhou, and their family members, about 330,000 of them, left Hubei province before the lockdown and joined in Wenzhou during the Chinese New Year (Tong *et al.*, 2020). The strong economic connection between Wuhan/Hubei and Wenzhou yielded in a large number of COVID-19 cases in Wenzhou, 504 cases, accounting for 24.3% and 41.5% of all cases in the YRD region and in Zhejiang Province, respectively.

Yuhuan County, the low-high outlier, was the only county with few cases although surrounded by the outbreak in Wenzhou. Located in a corner of the high-high cluster, Yuhuan cut off traffic from the surrounding areas uncompromisingly and prohibit people from traveling in and out. These strict control measures and the unique geographic location can explain the relatively small number of confirmed cases in Yuhuan.

The blue outlier of Hangzhou suggests a relatively high number of cases in the city, although surrounded by counties/districts of low case numbers. The reasons could be Hangzhou's provincial capital position as well as some unique events that affected the number of cases. Many travelers in and out of Zhejiang needed to transfer in Hangzhou. Additionally, according to the official notice of Zhejiang Health Commission, Hangzhou accepted several international flights that carried Hubei residents who traveled overseas but could not return to Hubei due to the strict travel ban. After the flights landed in Hangzhou, travelers with COVID-19 symptoms were immediately hospitalized. Residents of Wuhan were quarantined at Hangzhou airport hotels, and residents of other cities were placed under medical observation in Hangzhou for 14 days. As a result, Hangzhou had a high number of imported cases (63 cases) and consequently a high number of locally disseminated cases as well (91 cases), but the surrounding areas were not directly affected by the inflow of people.

Trend analysis of COVID-19 cases

We conducted a trend analysis for the YRD region and its three sub-regions and report the polynomial regressions that estimate the number of daily new cases in Figure 7. We observed the following: i) The quartic functions had the best model fit, with R^2 greater than 0.80, except for Zhejiang Province. ii) The inflection point had appeared in the YRD. For the whole region and Zhejiang Province, the inflection point occurred on February 3rd, 2020, and for



The start time of the gravity center analysis was January 23rd, when all three sub-regions started to have cases. We report the gravity center every other day to produce a legible figure. After February 20th, there were few cases, and thus we estimate the gravity center on the days with newly confirmed cases. Between March 4th and 10th, there were no new cases.

Figure 5. Changes of geographical gravity center of confirmed cases from January 23rd to March 4th, 2020.

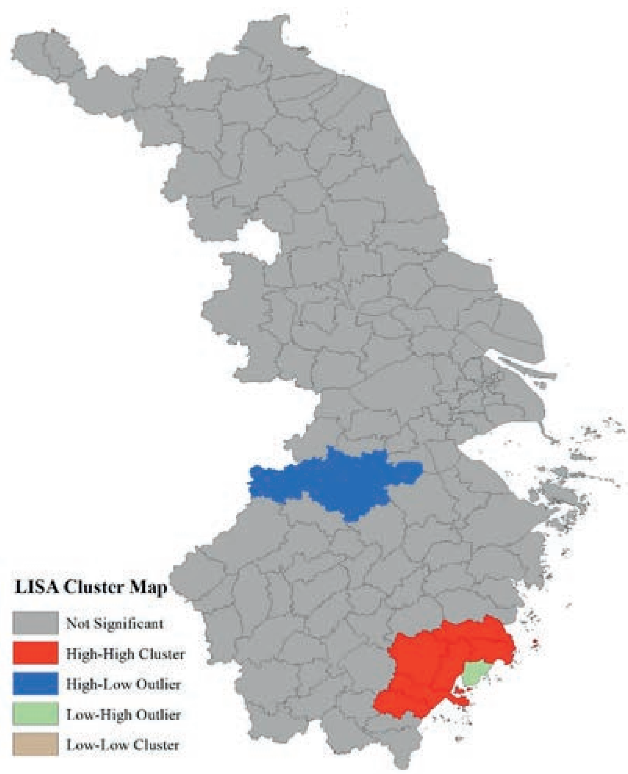


Figure 6. Local spatial autocorrelation (LISA) of the total number of confirmed cased in the YRD region.

Shanghai and Jiangsu Province, the inflection occurred on February 4th and February 6th, respectively. iii) The pandemic has been under control since February 21st, although fluctuations might still occur.

Our study has a few limitations. First, the research does not consider demographic profiles of COVID-19 patients or spatial characteristics of the places with high numbers of cases. Second, imported cases to China from other countries since March 2020 are not taken into consideration. Future studies should continue these important research areas.

Discussion

Our study used county/district level data from January 20th to March 10th 2020 (covering the outbreak and post-peak cycle in the YRD region) to analyze the spatiotemporal patterns and the temporal trend of COVID-19. The results are valuable for the formulation of targeted control measures based on relatively small geographic units over a period of a complete cycle.

The strict COVID-19 control measures worked in the YRD region. The number of newly added cases declined promptly and then stayed close to zero. From the temporal point of view, the number of imported cases in the YRD declined one week after Wuhan was locked down. Another week later, the number of locally disseminated cases peaked and then declined. Overall, the trajectory of the virus spread was reversed in the fourth week after as Wuhan and the whole of China implemented strict control measures. The spatiotemporal distribution of the total number of cases varied significantly at the county/district level. Since COVID-19 is transmitted through personal contact, population movements play an important role in its dissemination. Places with great population flow from Wuhan or Hubei Province as a whole tended to be significantly affected. Since northern and southern Zhejiang Province have convenient railways as well as strong economic connections with Hubei Province, especially Wuhan, these connections were the reason for the early great number of cases in those areas.

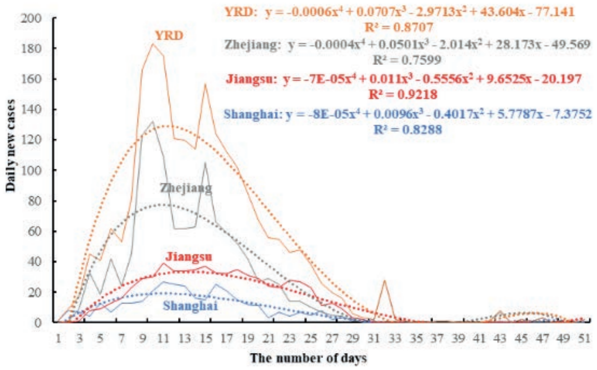


Figure 7. Polynomial Regression of daily new cases.

Conclusions

The analysis demonstrates that strict control measures effectively control the spread of the SARS-CoV-2 virus. However, even this good situation can be overwhelmed if the rapid development of the pandemic in other countries continues since the YRD region is one of the most open and mobile regions in China.

References

Backer JA, Klinkenberg D, Wallinga J, 2020. Incubation period of 2019 novel coronavirus (2019-nCoV) infections among travellers from Wuhan, China,20–28 January 2020. Euro Surveill 25: pii=2000062. doi:10.2807/1560-7917.ES.2020.25.5.2000062.

Basu S, Thibodeau TG, 1998. Analysis of Spatial Autocorrelation in House Prices. J Real Estate Finance Econ 17:61–85. doi:10.1023/A:1007703229507.

Brody H, Rip MR, Vinten-Johansen P, Paneth N, Rachman S, 2000. Map-making and myth-making in Broad Street: the London cholera epidemic, 1854. Lancet 356:64-8. doi:10.1016/S0140-6736(00)02442-9.

Chen Y, 2015. The distance-decay function of geographical gravity model: Power law or exponential law? Chaos, Solitons & Fractals 77:174-89. doi: 10.1016/j.chaos.2015.05.022.

Chowell G, Fenimore PW, Castillo-Garsow MA, Castillo-Chavez C, 2003. SARS outbreaks in Ontario, Hong Kong and Singapore: the role of diagnosis and isolation as a control mechanism. J Theor Biol 224:1-8. doi:10.1016/S0022-5193(03)00228-5.

Comber A J, Brunsdon C, Radburn R, 2001. A spatial analysis of variations in health access: linking geography, socio-economic status and access perceptions. Int J Health Geogr 10:44. doi:10.1186/1476-072X-10-44.

Cui J, Li F, Shi Z L, 2019. Origin and evolution of pathogenic coronaviruses. Nat Rev Microbiol 17:181-92. doi:10.1038/s41579-018-0118-9.

Di L, Feng B, Goosen TC, Lai YR, Steyn SJ, Varma MV, Obach RS, 2013. A perspective on the prediction of drug pharmacokinetics and disposition in drug research and development. Drug Metab Dispos 41:1975-93. doi:10.1124/dmd.113.054031.

Doll, R, 2008. The Prevention of Cancer: Pointers from Epidemiology. Routledge, 127pp.

Ecker DJ, Sampath R, Blyn LB, Eshoo MW, Ivy C, et al, 2005. Rapid identification and strain-typing of respiratory pathogens for epidemic surveillance. PNAS 102:8012-7. doi:10.1073/pnas.0409920102.

Forna A, Dorigatti I, Nouvellet P, Donnelly CA, 2020. Spatiotemporal variability in case fatality ratios for 2013–2016 Ebola epidemic in West Africa. Int J Infect Dis 93:48-55. doi:10.1016/j.ijid.2020.01.046.

Gao GF, 2018. From “A” IV to “Z” IKV: attacks from emerging and re-emerging pathogens. Cell 172:1157-9. doi:10.1016/j.cell.2018.02.025.

Gibbens JC, Wilesmith JW, 2002. Temporal and geographical distribution of cases of foot-and-mouth disease during the early weeks of the 2001 epidemic in Great Britain. Vet Rec 151:407-12. doi:10.1136/vr.151.14.407.

Ginsberg A, Spigelman M, 2007. Challenges in tuberculosis drug research and development. Nat Med 13:290-4. doi:10.1038

nm0307-290.
Gu CL, Zhu J, Sun YF, Zhou K, Gu J, 2020. The inflection point about COVID-19 may have passed. Sci Bull 65:865-7. doi: 10.1016/j.scib.2020.02.025.
Hilgenfeld R, Peiris M, 2013. From SARS to MERS: 10 years of research on highly pathogenic human coronaviruses. Antiviral Res 100:286-95. doi: 10.1016/j.antiviral.2013.08.015.
Kai F, 2020. Why is the pandemic so serious in Zhejiang and Henan? [Tencent website] Available from: https://xw.qq.com/amphtml/20200206A0C2EP00. [Website in Chinese].
Liang HG, Xue YJ, 2004. Investigating public health emergency response information system initiatives in China. Int J Med Inform 73:675-85. doi: 10.1016/j.ijmedinf.2004.05.010.
Liu Y, Li Y, Li ZL, Han FF, 2020. [Spread characteristics of COVID-19 epidemic situation in Guangdong Province]. Trop Geogr 4. Available from: https://mp.weixin.qq.com/s/qOYE_D_d2dHQ5xXcB0J_8A. [Article in Chinese].
Liu Z, Qian JL, Du YY, Wang N, Yi JW, Sun YR, Ma T, Pei T, Zhou CH, 2020. [Multi-level spatial distribution estimation model of the inter-regional migrant population using multi-Source spatiotemporal big data: a case study of migrants from Wuhan during the spread of COVID-19]. Journal of Geo-Information Science 22:147-60. doi: 10.12082/dqxxkx.2020.200045. [Article in Chinese].
Miao CH, Liu Y, Dong GP, Yang DY, Zhang H, Han YQ, Ren MH, Qi Y, 2020. [Preliminary Analysis on Spatiotemporal spread characteristics of COVID-19 epidemic in Henan Province. Collaborative Innovation Center of Yellow River Civilization]. Economic Geography 3. Available from: https://mp.weixin.qq.com/s/wSXBceS8_7QJ9kiOqnL4MQ. [Article in Chinese].
Max TA, Burkhart HE, 1976. Segmented polynomial regression applied to taper equations. Forest Sci 22:283-9. doi:10.1093/forestscience/22.3.283.
National Bureau of Statistics of China, 2020. [Forecast list of national GDP rankings in 2019]. Available from: https://www.stas.gov.cn. [Article in Chinese].
National Development and Reform Commission, 2010. Regional Development Plan of the Yangtze River Delta. Available from: http://www.gov.cn/zwgk/2010-06/22/content_1633868.htm.
Oparil S, Zaman MA, Calhoun DA, 2003. Pathogenesis of hypertension. Ann Intern Med 139:761-76.doi: 10.7326/0003-4819-139-9-200311040-00011.
Poirier C, Luo W, Majumder MS, Liu DB, Mandl K, Mooring T, Santillana M, 2020. The Role of Environmental Factors on Transmission Rates of the COVID-19 Outbreak: An Initial Assessment in Two Spatial Scales. Available from: https://ssrn.com/abstract=3552677 or http://dx.doi.org/10.2139/ssrn.3552677.
Reinhardt M, Elias J, Albert J, Frosch M, Harmsen D, Vogel U, 2008. EpiScanGIS: an online geographic surveillance system for meningococcal disease. Int J Health Geogr 7:33. doi:10.1186/1476-072X-7-33.
Rivas AL, Patron JF, Smith SD, Fasina F, Hittner JB, 2020. Geo-Temporal, Network Properties of the Chinese COVID-19 Epidemic (3/6/2020). Available from: https://ssrn.com/abstract=3551339.
Ross R, Glomset JA, 1976. The pathogenesis of atherosclerosis. N Engl J Med 295:369-77. doi: 10.1056/NEJM1976 0812295 0707.
Sanson RL, Liberona H, Morris RS, 1991. The use of a geographical information system in the management of a foot-and-mouth disease epidemic. Prev Vet Med 11:309-13. doi:10.1016/S0167-5877(05)80017-0.
Tong T, Ya W, Shuang Z, Di F, Chun J, 2020. [Why Wenzhou is the city with the most serious pandemic outside Hubei province?]. Available from: https://wxn.qq.com/cmsid/ 20200201A07I2V00. [Article in Chinese].
Wong G, Liu WJ, Liu YX, Zhou BP, Bi YH, Gao GF, 2015. MERS, SARS, and Ebola: the role of super-spreaders in infectious disease. Cell Host Microbe 18:398-401. doi: 10.1016/j.chom.2015.09.013.
Wuhan-Wenzhou Chamber of Commerce, 2020. Brief introduction of Chamber of Commerce. Available from: http://www.whswzsh.com/aboutus.asp?ID=10. [Website in Chinese]
Wu JT, Leung K, Leung GM, 2020. Nowcasting and forecasting the potential domestic and international spread of the 2019-nCoV outbreak originating in Wuhan, China: a modelling study. Lancet 395:689-97. doi:10.1016/S0140-6736(20) 30260-9.
Zhou F, Yu T, Du RH, Fan GH, Liu Y, et al, 2020. Clinical course and risk factors for mortality of adult inpatients with COVID-19 in Wuhan, China: a retrospective cohort study, 2020. Lancet 395:1054-62. doi: 10.1016/S0140-6736(20)30566-3.
Zhu N, Zhang DY, Wang WL, Li XW, Yang B, et.al, 2020. A novel coronavirus from patients with pneumonia in China, 2019. N Engl J Med 382:727-33. doi: 10.1056/NEJMoa2001017.