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Spatial Dynamics of COVID-19 Pandemic in China: Effects of Human Mobility and Control Measures

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Abstract: This study aims to analyze the spatio-temporal dynamics of COVID-19 pandemic in China, the heterogeneous effects of human mobility, and the effectiveness of prevention and control policies. Results show that leapfrogging spreading is dominant in the outbreak stage of the pandemic, whereas adjacent spreading is dominant thereafter. Their combination leads the pandemic to reach its peak, eventually forming three types of pandemic hot spots, namely, developed provinces and cities, surrounding provinces, and populous provinces. Moreover, early signs of pandemic import have been observed in the border areas. The return of long-term migrant workers and businessmen for family reunion in the Spring Festival and short-term business tour flow has heterogeneous effects on the development of the pandemic in different regions and various stages. The positive interaction between sanitary and anti-epidemic work and social governance system is the key to the success of pandemic prevention and control. Lastly, this research discusses the discipline advantages of geography in spatio-temporal dynamic analysis, key role of the structural analysis of human mobility in interpreting the epidemic spreading mechanism and building a public health emergency system, and importance of the complementary integration of big data and traditional data.

Keywords: **COVID-19 pandemic; human mobility; spatial dynamics; policy assessment; big data**

Dataset Availability Statement:

The dataset supporting this paper was published and is accessible through the *Digital Journal of Global Change Data Repository* at: https://doi.org/10.3974/geodb.2020.06.20.V1.

1 Introduction

As an urgent major public health event, the COVID-19 pandemic is a severe test of national and local governance capabilities[1]. When human-to-human spreading was confirmed on

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January 20, 2020, China took decisive measures, such as rapid first-class response on public health emergencies in all localities; closure of access to Wuhan and other cities; national deployment of medical staff, supplies and equipment; and implementation of fully or semi-closed management in all urban and rural communities[2]. With the joint effort of governments, societies, and residents, the COVID-19 pandemic reached its peak in early February and subsided at the end of the month in China. Evidently, China achieved a crucial victory in the fight against the pandemic in this stage[3]. The current focus of prevention and control has shifted to screening and controlling imported cases from overseas, and the normal prevention and control in social production and order recovery. The exploration on the cases in China, which has experienced the entire process from outbreak to control, will contribute to the global epidemic prevention and control, help deal with the spread of similar diseases effectively, and improve public health governance ability in the future[4].

The COVID-19 pandemic has attracted increasing attention from multiple disciplines[5]. However, several scientific issues have remained unsolved. In particular, research on the spatio-temporal dynamics of the pandemic and its formation mechanism from the perspective of geography is relatively scarce. First, epidemic maps are widely prevalent on social media, and have even become important social events. However, academic research on epidemics has seldom involved their spatial characteristics, and has insufficiently understood and summarized geographical distance, circle characteristics, and spatial patterns. In particular, these studies lack a spatio-temporal dynamics perspective. However, these studies have been indispensable links in the scientific understanding of the spreading mechanism of pandemics[6–7]. Second, the spatial movement of population is the main route of epidemic spreading. Numerous studies have focused on the role of this factor, and believed that human mobility can considerably explain the spread of pandemics[8–10]. However, the two patterns of human mobility, namely, long-term migration and short-term business tour, are generally confused in the related research, which has only focused on the total population but disregarded the characteristics of its internal structure. This mix will lead to biased explanation of epidemic spreading[11–12] and also form misleading social governance policies and recommendations. In addition, studies on policy influence have mostly been used to simulate epidemic situations[13–14], while the design and operation mechanism of specific policies are often excessively simplified. The result is difficulty in deeply evaluating the multi-level and diversified policy impact, which is not conducive to the summary of policy experience and optimization of future policies.

The objectives of this study are as follows: (1) describe the spatial-temporal dynamics of the spread of COVID-19 pandemic in China by using the daily data of all provinces (autonomous regions and municipalities directly under the central government, hereinafter referred to as the Province), (2) deeply explore the heterogeneous impact of various types of human mobility on the spread of the pandemic, and (3) analyze the differences and effectiveness of prevention and control policies issued by different cities in Hubei province of China.

2 Metadata of the Dataset

The metadata summary of the dataset[15] is summarized in Table 1. It includes the dataset full name, short name, authors, data year, data format, data size, data files, data publisher, and data sharing policy, etc.

Table 1 Metadata summary of the "Analysis dataset of COVID-19 spatial and temporal distribution with prevention and control effect under the population mobility in China (2020.1.19–2.22)"

Items	Description
Dataset full name	Analysis dataset of COVID-19 spatial and temporal distribution with prevention and control effect under the population mobility in China (2020.1.19–2.22)
Dataset short name	ChinaSpatialTemporalCOVID-19_2020.1.19-2.22
Authors	Liu, T., B-6318-2009, College of Urban and Environmental Sciences and Center for Urban Future Research, Peking University, liutao@pku.edu.cn Jin, Y. A., ABG-5542-2020, Center for Population and Development Studies, Renmin University of China, jinyongai0416@ruc.edu.cn Xiao, W., ABG-5448-2020, College of Urban and Environmental Sciences, Peking University, chloexiao@pku.edu.cn
Geographical region	China
Year	2020
Data format	.xls
Data size	122 KB
Data files	The dataset in .xls format is composed of seven tables of daily COVID-19 data from January 19 to February 22, which are respectively: 1) Daily new cases of COVID-19 in each province of China 2) Accumulative cases of COVID-19 in each province of China 3) Daily incidence rate of COVID-19 in each province of China 4) Accumulative incidence rate of COVID-19 in each province of China 5) Average number of days from the confirmed date to the starting date (Jan 19) in each province of China 6) Mean distance of confirmed COVID-19 cases to Wuhan 7) COVID-19 cases in layers by spatial adjacency with Hubei province
Foundations	National Natural Science Foundation of China (41801146); COVID-19 Special Fund of Peking University; Ministry of Education of China (18YJC840022); UKRI's Global Challenge Research Fund (ES/P011055/1)
Data publisher	Global Change Research Data Publishing & Repository, http://www.geodoi.ac.cn
Address	No. 11A, Datun Road, Chaoyang District, Beijing 100101, China
Data sharing policy	***Data*** from the Global Change Research Data Publishing &Repository includes metadata, datasets (in the *Digital Journal of Global Change Data Repository*), and publications (in the *Journal of Global Change Data* & *Discovery*). ***Data*** sharing policy includes: (1) ***Data*** are openly available and can be free downloaded via the Internet; (2) End users are encouraged to use ***Data*** subject to cita-tion; (3) Users, who are by definition also value-added service providers, are welcome to redistribute ***Data*** subject to written permission from the GCdataPR Editorial Office and the issuance of a ***Data*** redistribution license; and (4) If ***Data*** are used to compile new datasets, the 'ten per cent principal' should be followed such that ***Data*** records utilized should not surpass 10% of the new dataset contents, while sources should be clearly noted in suitable places in the new dataset[16]
Communication and searchable system	DOI, DCI, CSCD, WDS/ISC, GEOSS, China GEOSS, Crossref

3 Methods

3.1 Data Collection

The daily epidemic data used in this study came from the public data released by the provincial health commissions of all provinces. The number of newly confirmed cases in some provinces may be re-reported or missed in the process of data verification. Therefore, this index was not based on the original data, but it was obtained by subtracting the accumulative number of confirmed cases published on the day before from that on the current day. Previous studies have shown that after the peak of the COVID-19 pandemic in early February, the spatial pattern of the accumulative number of confirmed cases over the country has been stable. Further calculation has shown that after February 15, the correlation coefficient of the accumulative numbers of confirmed cases in all provinces was 1.000. Therefore, the end of study on the spatial-temporal dynamics of the epidemic situation was set as the following week (i.e., February 22). At that time, the number of newly confirmed cases in the majority of provinces of China has been reduced to zero.

The relevant indicators outside the pandemic were used in this study. The data sources were as follows. The indicator characterizing population migration refers to the population residing in Wuhan and other regions of Hubei province whose *hukou* (household registration) are registered in other provinces. The related data were from the distribution of floating population in Wuhan and Hubei province extracted from the individual database of the national 1% population sampling survey in 2015. Business tourist flow was characterized by the number of employees in star-grade hotels and railway passenger volume. The corresponding data were from the "China Statistical Yearbook". Moreover, the national migrants' dynamic monitoring survey data in 2017 released by the National Health Commission were used in this analysis. The survey represented the entire country, provinces, and major cities, with a sample size of approximately 170,000. The survey data were the most widely recognized and used by the academic community in the study on floating population.

3.2 Data Processing

On the bases of the daily accumulative and newly confirmed cases over the country, the main indicators in this study included the total number of cases and incidence rate. The meaning of the number of confirmed cases was based on the overall pressure brought by the pandemic on the local medical system and social government; this indicator would have an impact on social emotions and public opinion. Incidence rate was the ratio of the number of cases to the registered residence population, measured by the number of cases per million. The reason for selecting registered population as denominator in this research was that the COVID-19 pandemic coincided with the Spring Festival, and the majority of the floating population had returned home. Apart from business travellers of which the number was reduced drastically by the pandemic, some people settled in different regions would also return home for family reunion, thereby causing a difference between the registered and residential population during the Spring Festival and the epidemic season. However, this difference was substantially less than the scale of the floating population that returned home. Therefore, the registered population could better reflect the real population than the permanent population during the outbreak of the pandemic. The significance of the incidence rate was that it could not only statistically eliminate the impact of population size in different regions but also reflect the probability that people were infected in different regions, thereby presenting the risk and realistic effects of the pandemic on the people. In addition, the medical and governance resources in different regions were matched with the population size. This type of relative indicators can similarly reflect the pressure faced by the medical and governance systems.

To describe the spatial-temporal dynamics of the pandemic, this study adopted the weighted average method to calculate the two indicators. By using the number of daily confirmed cases as the weight, the daily average distance from the cases around the country to Wuhan was calculated, thereby reflecting the overall characteristics of the daily cases close to or far away from Wuhan (i.e., spatio-temporal evolution of the pandemic). By also using the number of daily confirmed cases as the weight, the average days from the date of confirmation to the starting date (January 19) of all cases around the country were calculated, thereby reflecting the overall temporal characteristics of the outbreak of the pandemic throughout the country (i.e., spatial diffusion process of the outbreak). The calculation formula is as follows:

$$D_i = \Sigma_j C_{ij} D_j \,/\, \Sigma_j C_{ij} \tag{1}$$

$$N_j = \Sigma_i C_{ij} N_i \,/\, \Sigma_i C_{ij} \tag{2}$$

where i refers to the date, j refers to the province, C_{ij} refers to the number of newly confirmed or accumulative cases in this province on that day, D_j refers to the straight line distance from the geometric center of province j to Wuhan, D_i refers to the average distance from the locations of the newly confirmed or accumulative cases around the country on day i to Wuhan, N_i refers to the days from day i to the starting date, and N_j refers to the average days from the confirmed dates of all cases to the starting date in province j.

Based on the spatial adjacency characteristics to Hubei province, provinces were divided into three circles, namely, first-level adjacency, second-level adjacency, and other provinces, in this study to calculate the daily changes of the pandemic-related indicators of all circles. This division reflected the characteristics of the circle structure in the epidemic spreading. A series of thematic maps and color scale charts of the epidemic situation change trend in different provinces were drawn to further investigate the spatial-temporal dynamic process of epidemic spreading at the provincial level. Based on scatter plot and multi-time point correlation analysis, the heterogeneous effects of population migration and business tour on the epidemic situation in different regions and its stage evolution characteristics were explained.

4 Data Results and Validation

4.1 Data Composition

The analysis dataset of COVID-19 spatial and temporal distribution with prevention and control effect under the population mobility in China (2020.1.19–2.22) includes seven tables of daily COVID-19 data from January 19 to February 22, namely 1) Daily new cases of COVID-19 in each province of China, 2) Accumulative cases of COVID-19 in each province of China, 3) Daily incidence rate of COVID-19 in each province of China, 4) Accumulative incidence rate of COVID-19 in each province of China, 5) Average number of days from the confirmed date to the starting date (Jan 19) in each province of China, 6) Mean distance of confirmed COVID-19 cases to Wuhan, and 7) COVID-19 cases in layers by spatial adjacency with Hubei province.

4.2 Data Results and Analysis

4.2.1 Distance and Circle

Distance is the epitome of spatial association. The spreading processes of many infectious diseases show adjacent spreading and distance decay. We calculate daily newly confirmed and accumulative cases, incidence rate, and the average distance to Wuhan; and analyze circle differences based on the spatial adjacent relationship between the different provinces and Wuhan. The results indicated that the transmission distance of the pandemic and circle dynamics are substantially more complicated than our expectation.

First, the pandemic pattern (with Wuhan as the center) exhibits a far-to-near process and near-to-far diffusion thereafter. As shown in Figure 1, the numbers of accumulative cases and newly confirmed cases and incidence rates indicated a dynamic rule that the distance from the cases to Wuhan descends initially and ascends thereafter. The early outbreak mainly occurred in Zhejiang, Guangdong, and other provinces that are considerably distant from Wuhan but have strong links with the city's business tour; and, eventually, in the neighboring provinces near Wuhan. When the pandemic lasted 10 days (i.e., since the end of

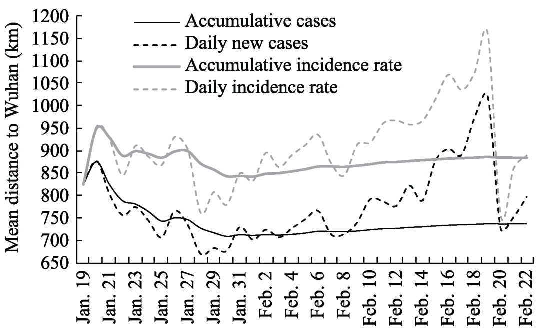

Figure 1 Mean distance from COVID-19-infected patients to Wuhan city

January), the distance from newly confirmed cases to Wuhan gradually increased, and the relative distance of the accumulative cases also began to increase thereafter.

Second, the average distance to Wuhan based on the incidence rate is farther than that based on the number of cases. This result reflected the fact that the actual spatial distribution of the pandemic is more balanced than the number of cases. The average distance from the provinces with weighted incidence rate to Wuhan is constantly higher than the weighted number of confirmed cases at each stage of the pandemic. In addition, this difference gradually increases from approximately 100 km to 150 km. This result also completely proved that the serious epidemic situation in the provinces around Hubei is substantially caused by the high density and large scale of population in these areas. In the later stage of the pandemic, the spatial pattern of the pandemic was extremely balanced and has nothing to do with the distance to Wuhan. Data presented in Figure 1 show that the weighted distance from all provinces to Wuhan, which is calculated by taking the corresponding incidence rate of newly confirmed cases as the weight, reaches approximately 1,100 km, which is markedly near the average geographical distance from all provinces to Wuhan. At this moment, the weighted distance calculated based on newly confirmed cases remained below 1,000 km. On the basis of the latter, the conclusion that the distribution of epidemic situation is close to Wuhan would still be obtained, forming public opinion and misleading policies.

Lastly, the correlation between spatial distance and pandemic is not high, and the explanatory power on epidemic spreading is limited. The correlation coefficient between the number of newly confirmed and accumulative cases in each province per day and the distance to Wuhan is generally below 0.6. After excluding the factor that the population size is generally large in the surrounding provinces, the correlation coefficient between the newly confirmed and accumulative incidence rates in each province per day and the distance to Wuhan is constantly below 0.45 which fails to pass the statistical test at the 1% significance level. In addition, the statistical results of many days cannot pass the test at the 5% significance level. Evidently, distance is not an important factor in the spread of this pandemic, of which the correlation is relatively weak. From the perspective of circle differences in the spatial adjacency relationship between each province and Wuhan, the developmental dynamics of the pandemic in all spatial circles are synchronous, thereby reflecting the effectiveness and necessity of national integrated prevention and control. Figure 2 shows that the newly confirmed cases start to rapidly grow on approximately January 22 in all circles. In the next 10 days (i.e., end of January and beginning of February), the epidemic situation reaches a peak and accumulated stable state. Thereafter, the newly confirmed cases in different provinces go into a downward range synchronously and experience approximately two weeks (i.e., around February 20), the newly confirmed cases in all circles go down to single digits. Only the special situation that occurred in Rencheng Prison in Shandong province caused the incidental rise of the sec ond-level neighbouring circle. In general, all circles experienced a rapid outbreak, rapid growth, and rapid decline, but synchronized at different stages. The effect of national integrated prevention and control is reflected from two angles. On the one hand, the period from the outbreak to the disappearance of the epidemic situation is approximately one month in all provinces, which is twice the incubation period of the virus. This result indicated that the epidemic situation has been inhibited effectively and efficiently after the outbreak, and the continuous transmission of the virus was well contained. On the other hand, the synchronization of the national epidemic situation showed that the population exchange scale among regions is not large, and no large-scale secondary transmission was observed from the area with serious epidemic situation to the surroundings. Owing to the small difference in the epidemic situation among different regions, the interregional secondary transmission was avoided successfully, even if human mobility was not completely cut off.

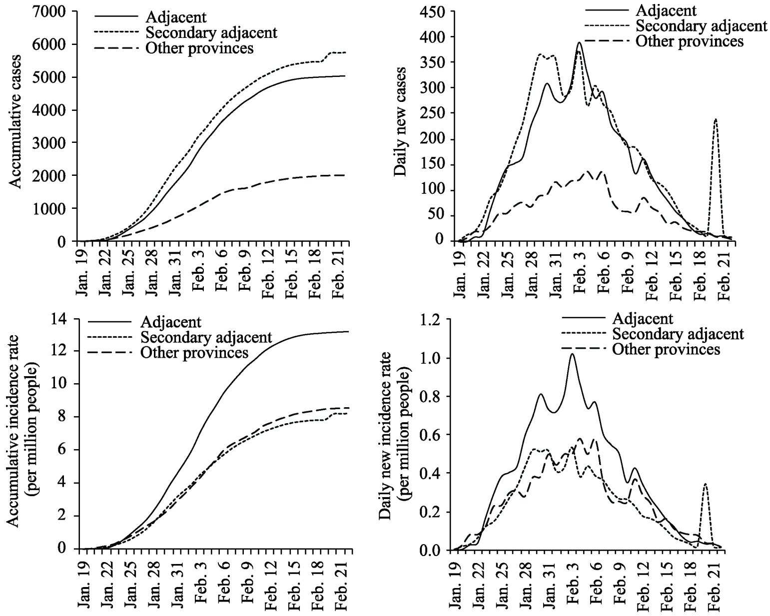

Figure 2 Comparison of the epidemic situations in three circles

The incidence rate in the province adjacent to Hubei is approximately 1.6 times that in other regions. Moreover, no difference was observed between the secondary adjacent provinces and other provinces. Among the three circles divided on the basis of the adjacent relations of Hubei with other provinces, the number of the confirmed cases in Anhui, Henan, Jiangxi, Hunan, Chongqing, and Shaanxi, which are primary adjacent to Hubei, approximated that in 12 provinces and districts that are secondary adjacent to Hubei (Table 2). On February 22 (i.e., end of the pandemic), 5,028 and 5,751 patients were accumulatively diagnosed respectively in the two circles. On February 3 (i.e., peak of the epidemic situation), 389 and 373 patients were diagnosed in the two circles, which were considerably close as well. However, the total population in the six provinces that are primary adjacent to Hubei is only 381 million, whereas that in the 12 provinces that are secondary adjacent to Hubei is approximately 697 million. Therefore, the similar number of confirmed cases does not reflect the similar severity of the epidemic situation in the two circles. Instead, the overall situation in the secondary adjacent provinces is considerably better than that in the primary adjacent provinces. After the impact of population size was excluded, the accumulative incidence rate in the secondary adjacent circle was approximately 8.3 per million people, which is substantially below that in the first adjacent circle (i.e., 13.2 persons per million people) and also slightly lower than the average level in other provinces (i.e., 8.6 per million people). The peak of the daily new incidence rate also shows a similar pattern. The peak values in the three circles are 1.02, 0.53, and 0.58 persons per million people.

Table 2 Comparison of the overall characteristics of the epidemic situations in three circles

	Registered population (100 million)	Accumulative confirmed cases (Feb. 22)		Peak of newly confirmed cases		
		Number	Incidence rate (per million)	Peak date	Number	Incidence rate (per million)
Primary adjacent	3.81	5,028	13.20	Feb. 3	389	1.02
Secondary adjacent	6.97	5,751	8.25	Feb. 3	373	0.53
Other provinces	2.56	1,997	8.58	Feb. 4	138	0.58

4.2.2 Dynamics of the Provincial Pattern

COVID-19 shows different spatial patterns in four stages, namely, outbreak, development, peak, and subsiding. In general, the pattern is not a core-peripheral one but much more complex than that. It reflects the multiple factors underlying the epidemic spreading. At the outbreak stage, the impact of leapfrogging spreading on epidemic hot spots is higher than that of adjacent spreading. From the epidemic pattern map on January 25 (Figure 3), the first-batch outbreak sites outside Hubei province include Zhejiang, Guangdong, Hainan, Beijing, and Shanghai. Zhejiang is the first province with confirmed cases exceeding 100 and the number of confirmed cases in Guangdong also reached 98. The initial incidence rate in these areas was substantially higher than that in the provinces around Hubei province. Only in Chongqing did the outbreak comes early. The common characteristics in the sites where the pandemic outbreaks in the early stage are that these sites are economically devel oped, with the national-level super large central cities or hot places for travelling, and they all have close business tour links with Hubei and Wuhan.

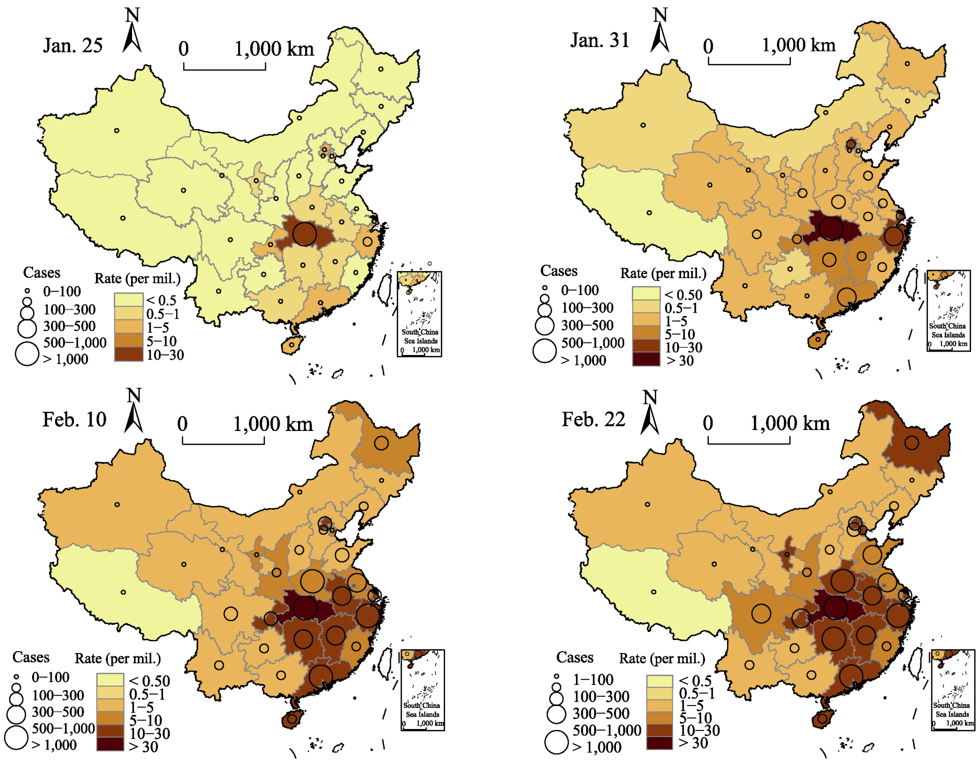

Figure 3 Spatial distribution of cases and rate of the COVID-19 pandemic in China from Jan. 25, 2020 to Feb. 22, 2020

At the second stage in the epidemic development, hot spots with leapfrogging spreading are continuously enhanced, while the effect of adjacent spreading begins to appear. By the end of January, Beijing, Shanghai, Zhejiang, and Guangdong continue to experience the most serious pandemic, as the accumulative incidence rates in Beijing, Shanghai, and Zhejiang are at over 10 persons per million people, and the number of confirmed cases in Zhejiang and Guangdong exceeds 500. All of these breakthroughs occur in hot spots with leapfrogging spreading. Moreover, the epidemic situation in the provinces and cities around Hubei province developed rapidly. In Hunan, Jiangxi, and Chongqing, the accumulative incidence rates were over 5 persons per million people, and the confirmed cases in Henan and

Hunan were 422 and 389, respectively, second only to Zhejiang and Guangdong. The hot circle is initially formed around Hubei province. However, the characteristics of this type of circle are not typical. On the one hand, the epidemic situation in Anhui and Shaanxi adjacent to Hubei was not more serious than that in other provinces. On the other hand, the epidemic situation developed rapidly in Shandong, Jiangsu, Fujian, and Sichuan not adjacent to Hubei.

At the third stage when the pandemic is at the peak, two dominant modes, namely, leapfrogging and adjacent spreading, show a balanced state. After the peak period in the early February, the epidemic situation in the provinces around Hubei was completely shown, while the epidemic situation in leapfrogging hot spots formed in the beginning remained outstanding. From the accumulatively confirmed cases, Guangdong, Zhejiang, and Henan became the top three provinces with confirmed cases over 1,000, followed by Hunan, Anhui, and Jiangxi around Hubei province, with confirmed cases of over 800. From the incidence rate per million people, the top three provinces over 20 remained Beijing, Shanghai, and Zhejiang, and the incidence rates in Guangdong and Hainan also exceeded 10. At this time, the incidence rates in Jiangxi, Chongqing, Hunan, and Anhui around Hubei also remained over 10 persons per million people. Evidently, the hot adjacent circle was formed.

In the fourth stage when the pandemic is gradually subsiding, the final epidemic pattern has four typical characteristics. First, the areas with the most serious epidemic owing to leapfrogging spreading include Beijing, Tianjin, Shanghai, Zhejiang, Guangdong, and Hainan. Second, the epidemic situation in the provinces around Hubei province was generally serious, and the majority of them have large population and numerous infected people, forming an adjacent circle with high incidence of epidemic. Among them, the accumulative number of confirmed cases in Henan, Hunan, Anhui, and Jiangxi, which have large population, has reached or has been close to 1,000, ranking in the top six. Chongqing's population base is relatively small, but there were 573 confirmed cases, ranking ninth. The incidence rates per million people in the five provinces and cities were over 10. Third, the epidemic situation in Shandong, Jiangsu, Sichuan, and other provinces with large population is also worthy of attention. The incidence rates in these provinces were in the middle level, but the confirmed cases were over 500 owing to their large population, ranking in the top 10. Fourth, Heilongjiang is a unique province with incidence rate in the top 10, excluding the first two types of hot spots. Early signs showed careless omission in its border control. Since the outbreak of the pandemic, the incidence rate has been increasing continuously, and entered the top 10 in the first half of February. Owing to Heilongjiang's remote location, small population base, and slow release of epidemic information from neighboring Russia, the severity of the epidemic situation in this province did not attract sufficient attention for a long time, resulting in serious consequences.

Based on the average days from the confirmed date of all cases in different provinces to the starting day, the corresponding average diagnosed days in different provinces were obtained. The overall characteristics of the development of epidemic situation in various regions and the regularity of the change in the epidemic situation in China can be found. The results in Figure 4 show the following characteristics. First, the development of the epidemic in various regions was highly synchronous, and the average diagnosed time of cases in nearly all provinces was in the first 10 days of February, particularly in the third to the fifth days. It coincides with the law of circle division shown in Figure 2. That is, the synchronization law is not only reflected among the circles but also occurs in the majority of provinces, thereby reflecting the national integrated prevention and control strategy and its effectiveness. Second, the average diagnosed time in the provinces adjacent to Hubei province was highly consistent. Only in Hunan province, which has the closest contact with Hubei province and the strictest prevention and control measures, and Shaanxi province where the epidemic situation was consistently not severe, the average diagnosed time was one day earlier than the other four provinces and cities. Third, no circle characteristic was evident in the secondary adjacent and other provinces, but the interprovincial differences are evident.

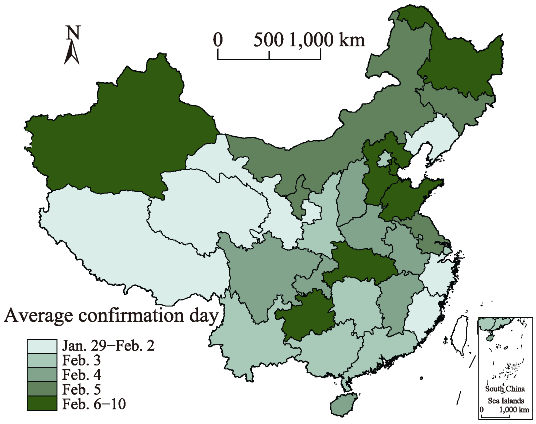

Figure 4 Average diagnosed date of confirmed cases in provinces of China

5 Impacts of Human Mobility on the Spatial Dynamics of the Pandemic

Similar to most infectious diseases, the main route of rapid spreading of COVID-19 is people-to-people transmission. Personnel exchange between the epidemic center and all regions is the key factor of epidemic situation. Note that mobility has numerous forms, including long-term migrant workers and businessmen, as well as short-term business, tourism, family visits. The mobility behavior of various groups has different impact on the spread of the epidemic, which needs to be investigated separately.

5.1 Migrants in Hubei Province

The outbreak of COVID-19 happened during the Spring Festival. Long-term migrant workers returning home for the Spring Festival may be an important means for the spread of the epidemic. Figure 5 shows the relationship between the number of registered population in each province migrating to Wuhan and other cities of Hubei and the accumulative cases in the province. First, the long-term connections of various provinces to Wuhan and other cities of Hubei in the population have strong explanatory power for the epidemic situation. Evidently, exclusively focusing on Wuhan will be insufficient to explain the impact of population returning to their hometown on the spread of the epidemic. Second, the preference of population migration for spatial proximity is the main formation mechanism of spatial distribution pattern of epidemic situation. On the one hand, provinces around Hubei are the major sources of migrants in Wuhan and Hubei provinces. The close population connection leads to the most serious epidemic situation in the adjacent circle. On the other hand, the epidemic situation was considerably minor in Jilin, Ningxia, Inner Mongolia, Tibet, and Qinghai. Guangdong and Zhejiang are the two provinces with the most serious deviation from the fitting line. That is, the explanatory power of the total migrants remained insufficient, and the influence of the internal structure of migrants or short-term mobility cannot be disregarded.

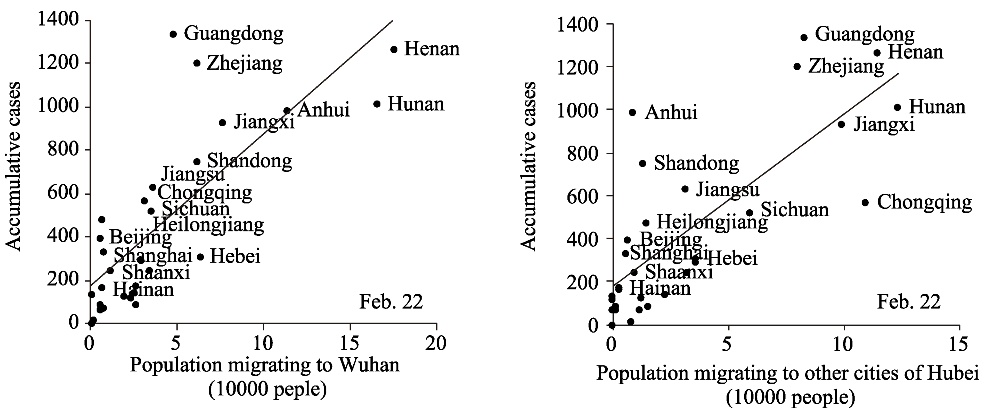

Figure 5 Relationship between the migrating population in provinces to Wuhan and other cities of Hubei and the number of COVID-19 confirmed cases

5.2 Business People Residing in Hubei Province

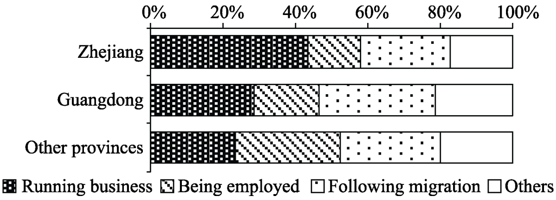

Figure 6 Reasons for registered population in various provinces migrating to Hubei

The registered population in Guangdong and Zhejiang who have resided in Wuhan or other cities in Hubei is less than that in Hunan, Jiangxi, Anhui, and other provinces around Hubei province, although the epidemic situation is more serious than that in the latter. This dislocation urged us to further examine the causes of population migration and mobility. Accordingly, the majority of the people from Wenzhou, Taizhou, and other places of Zhejiang are in business, and minimal workers are employed. The evidence is found from the data from migrant dynamic monitoring survey in China released by the National Health Commission (Figure 6). Among the Zhejiang people floating to Hubei, 57.4% are in business and 22.9% are workers engaged in the industrial work. The corresponding ratio is 2.51. However, the ratio for all migrants in Hubei is only 0.84. It is 1.60 for those from Guangdong, which is twice that from other places to Hubei. Migrant workers and businessmen are both long-term migrants of Hubei. However, compared with migrant workers, businessmen have higher impact on the spread of the epidemic, even though their absolute scale is small. On the one hand, businessmen are likely to have extensive contact with the local people in the outbreak area, and the probability of being infected is extremely high. On the other hand, businessmen have strong local mobility after returning to their hometowns, with numerous visits to relatives and friends in a wide range. Therefore, their infectivity is substantially higher than that of migrant workers. Based on the analysis on the long-term migrants in Hubei province, we can provide an effective explanation on the spreading mechanism of COVID-19 in Guangdong and Zhejiang, where the population scale migrating to Hubei is not high but the outbreak of epidemic situation is the earliest and most serious.

5.3 Short-term Business Travelers

Short-term intercity business tour is also a factor that cannot be disregarded. The number of employees in star hotels and railway passenger volume are used to characterize the intensity of population flow for business and tourism, and to investigate its relation with the number of confirmed cases. Similarly, a significant linear correlation was found. The correlation coefficients are 0.45 and 0.60, respectively. It is extremely close to the influence degree of long-term migration (Figure 7).

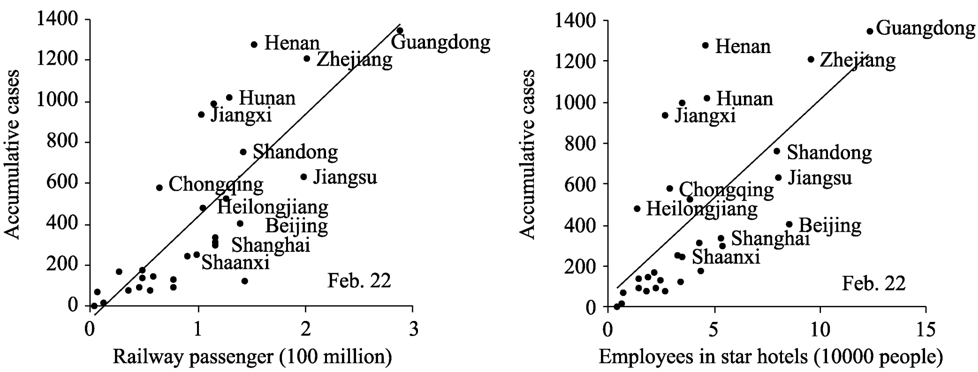

Figure 7 Relationship between the number of railway passenger and employees in star hotels, and number of COVID-19 confirmed cases

Therefore, people in outbreak areas going to other areas of the country for business and tourism should be another factor leading to the spread of the virus. Evidently, Guangdong is the most typical. Although the scale of floating population from Guangdong to Wuhan and Hubei province is not prominent, and the proportion of long-term businessmen in Hubei province is lower than that in Zhejiang province, the number of COVID-19 confirmed cases is extremely high. Its position as a business and tourism center plays a significant role in the spread of the epidemic. This case is a typical case of short-term population mobility driving the spread of the epidemic.

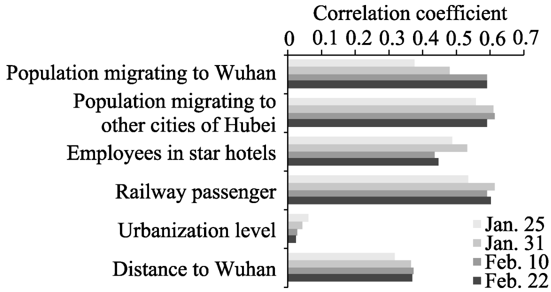

Figure 8 Changes in the correlation between population-related indicators and epidemic situation

5.4 Stages of the Impact of Various Types of Population Mobility on the Epidemic

The relationship between the long- or short-term population mobilities and the spread of the epidemic is stable and dynamic (Figure 8). First, long- and short-term population mobilities have similar explanatory power to the spread of the epidemic. The correlation coefficients between the two groups of indicators and accumulative number of confirmed cases in different regions are extremely close. Thus, we should not disregard them in the analysis of the epidemic spreading mechanism. Second, the explanatory power of the population connections in different regions with Wuhan continues to increase, but the influence of population connections with other cities and prefectures in Hubei remains stable. The overall explanatory power of the latter is even stronger than that of the former. It can be seen that the spread of the epidemic in Hubei province was hardly under effective control in the early stage. However, long-term migrant workers and businessmen returning from Wuhan experienced a relatively long incubation period, which may be related to the severity of the epidemic situation in Wuhan. In addition, the explanatory power of the distance to Wuhan to the distribution pattern of the epidemic situation is constantly lower than that of various population mobility indicators. Evidently, the important aspect behind spatial distance is the personnel exchange between regions. Lastly, the impact of urbanization level on the number of confirmed cases in various regions is markedly small and constantly decreasing, thereby reflecting that the localization spreading of the virus has been effectively controlled through out the country. Moreover, there is no situation that the denser the living form of population, the more serious the epidemic situation.

6 Policy Analysis: Using Cities in Hubei as Examples

The effective management and control of inter- and within-city population mobilities was the key reason for the rapid control of COVID-19 pandemic in China. However, the strength and effectiveness of the control still have local differences. We combed and analyzed the population mobility control policies in Wuhan and other cities and prefectures of Hubei. On the one hand, the result can explain the relationship between the prevention and control measures in these areas with serious pandemic and local epidemic situations. On the other hand, it can also further explain the spatial-temporal dynamics of the national epidemic situation caused by the aforementioned population mobility from Hubei to other provinces and cities.

6.1 Prevention and Control Policies and Dynamics of the Epidemic Situation in Wuhan

By combing the related major events based on the time line, we can summarize the key time points in the control process of the pandemic and the change of control strategies in Wuhan.

Compared with the curves of Wuhan's epidemic situation, we can further evaluate the prevention and control, which can provide reference to cope with public health events.

The first critical period of the policy was on January 20 to 23, when China faced up to the pandemic with a scientific attitude and immediately formed a high consensus on the comprehensive anti-epidemic with the Wuhan lockdown as the key node. Before January 19, people had few sense of self-protection. On January 20, Mr. Zhong, N. S., an academician, said that COVID-19 had certain human-to-human spreading, and the community started to become alert. On this day, Chairman Xi, J. P. made an important instruction to prioritize the people's safety and health, formulate an effective program, and organized all sides to take prevention and control measures to resolutely curb the spread of the pandemic. In No.1 official document released by the National Health Commission in 2020, the pneumonia caused by COVID-19 was included in Class B infectious diseases, stipulated in the Law of the People's Republic of China on the Prevention and Treatment of Infectious Diseases. The prevention and control measures for Class A infectious diseases were taken. Since then, the number of newly confirmed cases have been summarized and released daily. Moreover, COVID-19 prevention and control headquarters were established in Wuhan. On January 23, airports, railway stations, and other channels were closed, and Wuhan was placed on lockdown. The spread of the epidemic was controlled with unprecedented powerful means. On the same day, Wuhan made a decision to build Huoshenshan Hospital. Moreover, political decision-making at the highest level, scientific judgments of top medical experts, and the information disclosure attitude of competent departments have achieved key effect. That is, governments at all levels and people from all walks of life immediately reached a consensus on comprehensive anti-epidemic actions. Hence, the cohesion of national consensus is crucial for epidemic prevention and control.

The core work in the second stage is to establish a scientific and effective epidemic prevention and control system, which took approximately two weeks, from January 24 to February 6. After a comprehensive anti-epidemic consensus was reached, Wuhan also became the focal point of the central and local governments' response strategies, and various anti-epidemic measures were frequent. Therefore, these seemingly chaotic strategies essentially focused on three major tasks for the prevention and control of the epidemic: collecting and isolating patients, cutting off the spreading routes, and protecting susceptible people. Consequently, a scientific and effective prevention and control system was gradually established. Based on Huoshenshan Hospital, the Wuhan government decided to build Leishenshan Hospital on January 25. The two hospitals were officially opened on February 4 and 8 respectively. On January 24, the first batch of military and provincial/municipal medical teams went to Wuhan, and some provinces successively provided support to ensure the admission and treatment ability in Wuhan. On February 2, Hubei announced that all suspected cases were centralized, and forced those cases that refused to be isolated. On February 3, Cabin Hospital was established in Wuhan for patients with mild symptoms, and started operations two days later. In terms of cutting off the spreading routes, all types of passenger traffic in Wuhan were suspended on January 23. On January 26, automotive vehicles were prohibited in the central districts. On February 2, troops stationed in Hubei began to distribute and supply living materials for Wuhan citizens. In terms of protecting susceptible people, 132 isolation facilities were established in Wuhan on February 4. Since February 6, the body temperature monitoring has been carried out in Wuhan. Thanks to the trust and support of the entire society, medical and construction teams from all over the country fought side by side with Wuhan citizens, making all measures to be effectively implemented.

The policies at the third stage focus on the improvement of prevention and control measures, and the stabilization of social order, which lasted for approximately two weeks until February 19. On the one hand, we should strictly implement and constantly improve the prevention and control system in the form of a protracted war. On February 7, the National Health Commission announced a new rescue model. A total of 16 provinces were asked to provide support in the form of one province-to-one city. The unified scheduling was changed to counterpart assistance, giving full play to the enthusiasm and creativity of local governments. By February 10, 19 provinces have provided one-to-one support. On February 11, all residential districts of the city were under the closure management, which was extended thereafter to all urban and rural communities on February 16. On February 17, strict management measures for closing public places were formulated. On the other hand, social concerns were actively responded and social emotions and order were stabilized. On February 7, the death of Li, W. L. was identified as an occupational injury. The State Committee of Supervisory went to Wuhan to conduct a comprehensive investigation. On February 8 and 13, the main leaders of Hubei province and Wuhan were re-arranged. The epidemic situation should be further investigated, hospitals must be constructed, the number of beds should be increased. In the middle of February, a phenomenon that the beds in hospitals were waiting for patients has been achieved, thereby indicating that the epidemic prevention and control has won the spread of the epidemic.

The fourth stage started from late February. The policy was improved and the epidemic situation was stabilized. Social order was restored in early March. On March 8, newly confirmed and suspected cases in Hubei, excluding Wuhan, were cleared to zero. After 10 days, the newly confirmed cases in the entire province were cleared for the first time, and the cases appeared rarely. On March 11, Hubei started to implement differentiated prevention and control in different areas at varying levels, and enterprises resumed work and production conditionally based on the categories of enterprises and time. On March 17, medical teams from different provinces began to evacuate from Hubei. On March 25, the control measures for the passageways, excluding Wuhan, were relieved. On April 8, the control measures for the passageways of Wuhan were relieved. On April 26, Wuhan's COVID-19 patients staying in hospital were cleared to zero. In middle and late May, 9.9 million people in Wuhan received nucleic acid testing, and no confirmed case was found.

The COVID-19 cases curve in Wuhan considerably reflects the changes of the aforementioned prevention and control polices, and directly shows the mistakes and results of the epidemic prevention and control (Figure 9). The early avoidance and concealment of the COVID-19 pandemic leads to two important consequences, making the later epidemic prevention and control policy must be systematic and strict. First, a large-scale infected population has been formed. The early concealment has gradually emerged in the late stage. It poses a great and continuous pressure on the medical system. Second, in case of insufficient preparation, the medical treatment system is in disorder and the social policy lacks trust foundation. Third, the extension of the epidemic spreading chain was controlled owing to the constant improvement and persistence after the establishment of the prevention and control systems. The infection is limited to family infection within the incubation period, and there is no social aggregation infection and the second peak of the epidemic situation. Lastly, a good interaction between the society and medical system is critical. Social trust can be rebuilt rapidly, which ensures social stability and universal support from all people. The medical and infectious disease prevention and control systems have also given a rapid response, and both of them support each other and guarantee each other. This aspect may be the key to the success of epidemic prevention and control in Wuhan and even the entire country.

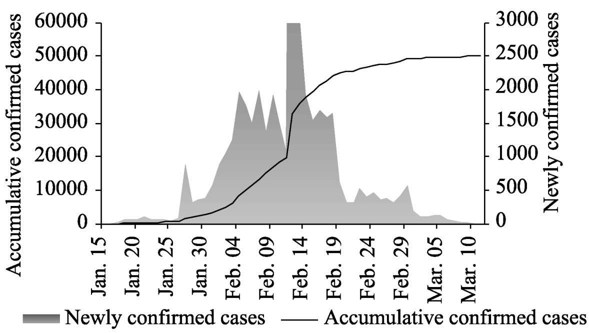

Figure 9 Dynamic curves of the epidemic situation in Wuhan from Jan.15, 2020 to Mar.10, 2020

6.2 Coping Strategies and Epidemic Situation among Cities in Hubei Province

The control effects of various cities in Hubei province are evidently different. The time when measures are taken at the municipal level, strength and intensity for implementing measures and the follow-up policies adapted to local conditions are the key factors to explain the differences in the effectiveness of epidemic prevention and control.

As of April 26, the number of patients staying in hospitals in Wuhan has been cleared to zero. The proportion of accumulatively confirmed cases in cities and prefectures in Hubei to the registered population, also called incidence rate, is shown in Figure 10. The incidence rate of Wuhan is 53.5 persons per 10,000 people, ranking first, followed by Ezhou, with 12.4 persons infected per 10,000 people. Xiaogan city is the third. Ezhou and Xiaogan are close to Wuhan. The last three cities are Qianjiang, Shennongjia district, and Enshi prefecture. Shennongjia district is located in the deep mountains, sparsely populated, and it is reasonable that the infection rate is low. However, Qianjiang, as a densely populated city with convenient transportation, and only 150 km to Wuhan, ranks last but second in incidence rate. It is difficult to explain with some indicators, such as human mobility and economic exchanges with Wuhan. Enshi prefecture is distant from Wuhan and is mainly mountainous. However, it is one of six prefecture-level cities with population of over 4 million. Approximately 100,000 migrant workers in Wuhan are from Enshi. The difference in the prevention and control measures may be one of the important reasons for the varying incidence rates.

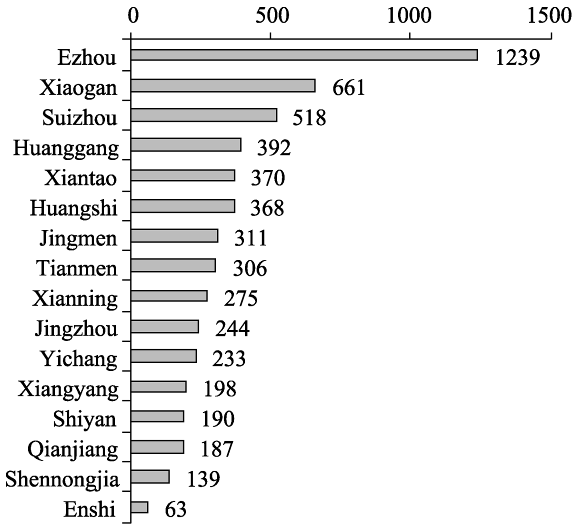

Figure 10 Incidence rates of COVID-19 in cities in Hubei province, excluding Wuhan (per million people)

The strong and powerful control of the epidemic situation in Hubei started from the city closure, which was widely implemented in all areas of the province. However, the implementation time varied. As early as January 17, Qianjiang was closed and people were grounded and required to be isolated at home. Meanwhile, patients were immediately admitted and quarantined. Owing to these immediate and powerful measures, the result of epidemic prevention and control in Qianjiang is remarkable. Therefore, Qianjiang is the city around Wuhan with the lowest incidence rate, and also one of the cities with the mildest epidemics in the province.

The infection and mortality rates in Enshi prefecture were extremely low, in the forefront of the province. There were a total of 4.01 million registered population in the entire prefecture (based on 2017 statistics). Only 252 cases confirmed and 7 deaths during COVID-19 pandemic. It also considerably benefitted from high alertness and powerful treatment and prevention and control measures. A field investigation by the authors indicated that the management and control of human mobility and epidemic situation at the level of urban and rural community was strict and effective. Particularly in rural areas, the publicity, investigation, and access control measures with a village as the unit have been strictly implemented. Enshi prefecture attaches considerable importance to the dynamic adjustment of epidemic prevention and control policies and the formulation and implementation of supporting policies. For example, while carrying out full-close management in all villages, the town government uniformly distributes living materials, from registration for buying anti-cold drugs to selling anti-cold drugs for cough and fever all over the prefecture.

7 Discussion and Conclusion

Based on the daily epidemic data of China, this study describes the spatial-temporal dynamics of COVID-19 pandemic in China, examines the heterogeneity impact of human mobility patterns on the spread of the epidemic, and analyzes the differences and effectiveness of epidemic prevention and control policies by taking different cities and prefectures in Hubei province as examples. The research results are as follows. (1) The spatial dynamics of the pandemic is not the core peripheral structure dominated by adjacent spread, but the result of multiple spatial patterns being mixed, thereby reflecting the multiple factors and motive force of epidemic spread. Leapfrogging spreading is dominant in the outbreak stage of the pandemic, and adjacent spreading is dominant later. Their combination promotes the pandemic to reach the peak, and three types of pandemic hot spots, such as Beijing, Tianjin, Shanghai, Zhejiang, Guangdong and other highly developed areas, surrounding provinces, and populous provinces, are eventually formed. In addition, there have been signs of pandemic import early in the northeast border areas. (2) The association between spatial distance with the epidemic situation is not high. The epidemic pattern is mainly affected by human mobility. The homecoming of long-term migrant workers and businessmen and the short-term business tour flow have heterogeneous effects on the development of pandemic in different regions and different stages. Only by combining the structural analysis of population with the spatial-temporal dynamic analysis of epidemic situation can we effectively explain the spread mechanism and control effect of the pandemic. (3) The analysis on the differences in the prevention and control policies and the epidemic situation among cities and prefectures in Hubei province shows that the timeliness, scientificity, systematicness, and sustainability of epidemic prevention policies are indispensable; and social stability supported by trust and national participation are also indispensable. The key to the success of epidemic prevention and control lies in the positive interaction between health care and social governance system.

The preceding conclusion also present points to ponder. First, there is an essential difference between simple and intuitive epidemic map and rigorous and in-depth spatial and temporal dynamic analysis. The latter requires the professional analysis of geographers, who can find and summarize the characteristics and laws of epidemic spread, and have a direct and profound understanding of the epidemic spreading mechanism, thereby reflecting the discipline advantages of geographical spatial analysis.

Second, human mobility driving the spread of virus is the basic route for the spread of the epidemic. Scientific research will not remain in this simple correlation. Only by deeply analyzing the structural characteristics of human mobility can we truly understand the mechanism of epidemic spread and explain the temporal and spatial dynamics of epidemic situation. It is particularly important to distinguish between long-term permanent migration and short-term daily business tour flow. The former can affect the spread of the pandemic only at the specific time point of homecoming during the Spring Festival, and poses a serious impact in the main inflow and outflow places. However, the latter may pose an impact in any time and place. Accordingly, migrant workers and businessmen should not be the focus of epidemic prevention and control, and they should not be excluded by the institution or society. The daily business tour flow is the key group of concern in the development of public health emergency response system.

Lastly, this study analyzes the spatial-temporal dynamics of epidemic situation by using big data, and makes an effective explanation by using statistical data and survey data, which can be regarded as an attempt to combine big data with traditional data. The authors' related research also reveals that the interpretation of Baidu migration and other data on the dynamics of epidemic situation is not better than that of the traditional data. Relatively, the former has higher timeliness, which is conducive to the analysis on temporal and spatial dynamics; the latter with more rich indicators can support the structural analysis of human mobility, and explain the dynamic of epidemic situation more deeply[17]. The cases for epidemic analysis completely show no difference between big data and traditional data in advantages and disadvantages, and also no mutual exclusion. The deep integration and complementary advantages of both are important for the study of social science.

Author Contributions

Liu, T., and Jin, Y. A. designed the algorithms of dataset. Xiao, W., Chen, J. C., and Liu, T. contributed to the data processing and analysis. Liu, T., Chen, J. C., and Jin, Y. A. wrote the data paper.

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