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Universal scaling of human flow remain unchanged during the COVID-19 pandemic

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Abstract

To prevent the spread of the COVID-19 pandemic, governments in various countries have severely restricted the movement of people. The large amount of detailed human location data obtained from mobile phone users is useful for understanding the change of flow patterns of people under the effect of pandemic. In this paper, we observe the synchronized human flow during the COVID-19 pandemic using Global Positioning System data of about 1 million people obtained from mobile phone users. We apply the drainage basin analysis method which we introduced earlier for characterization of macroscopic human flow patterns to observe the effect of the spreading pandemic. Before the pandemic the afternoon basin size distribution has been approximated by an exponential distribution, however, the distribution of Tokyo and Sapporo, which were most affected by the first wave of COVID-19, deviated significantly from the exponential distribution. On the other hand, during the morning rush hour, the scaling law holds universally, i.e., in all cities, even though the number of moving people in the basin has decreased significantly. The fact that these scaling laws, which are closely related to the three-dimensionality structure of the city and the fractal structure of the transportation network, have not changed indicates that the macroscopic human flow features are determined mainly by the means of transport and the basic structure of cities which are invariant of the pandemic.

Keywords: GPS data, City structure, Power law, Scaling relations

Introduction

Since the initial case of infection was confirmed at the end of 2019 <https://www.who.int/emergencies/diseases/novel-coronavirus-2019/events-as-they-happen>, COVID-19 pandemic has been spreading rapidly all over the world <https://covid19.who.int/> and seriously affecting the entire socio-economy such as finance (Goodell 2020; Ashraf 2020), education (Marinoni et al. 2020; Pragnolapati 2020) and people's taste (Ding et al. 2020). As it is well known, human movement play a crucial role in the spread of infection (Tizzoni et al. 2014; Viboud et al. 2006; Balcan et al. 2009; Hufnagel et al. 2004; Colizza et al. 2007; Giles et al. 2020; Gross et al. 2020), and many governments have blockaded cities and restricted individual mobility. Evaluation of human mobility using individuals location data has been studied for Italy during spreading of COVID-19 (Pepe et al. 2020), and there exist many studies, focusing on the changes in human mobility patterns due

to the effects of stay-at-home order in each country (Jeffrey et al. 2020; Lutu et al. 2020; Gao et al. 2020; Huang et al. 2020; Yabe et al. 2020; Bonaccorsi et al. 2020; Engle et al. 2020; Jia et al. 2020; Orro et al. 2020). In the United Kingdom, the mobility of people after the Prime Minister's announcement of an enforced lockdown has decreased significantly (Jeffrey et al. 2020). There has been found a slight difference in the median number of trips between high population density areas and low population density areas, which reflect a decrease in the number of people heading to the city center. In Italy's national lockdown, the relationship between economic variables and mobility change has been reported, and the results suggest that the lockdown unequally influences the poor (Bonaccorsi et al. 2020). In the United States, the human mobility during the pandemic has decreased significantly on average, but there was a temporarily marked increase in mobility due to the protest demonstration against racism that began with the death of Mr. George Floyd (Huang et al. 2020). In Japan, the number of railway users has decreased significantly, and since the declaration of emergency, the number of station users during peak hours in April and May has declined by 70% compared to normal times https://www.mlit.go.jp/tetudo/tetudo_fr1_000062.html. Despite the non-compulsory measures, the radius of gyration decreased to 50% of the typical and the social contact index reached 30% of normal times by April 15th (Yabe et al. 2020).

In this paper, we analyze human movement patterns during the COVID-19 pandemic from a new viewpoint that focuses on synchronized human flow patterns rather than individual trajectories. Recently, we have developed and applied a new concept of drainage basins analysis in analogous to river flow patterns (Takayasu and Inaoka 1992) to GPS data of 2015 and revealed several universal scaling laws about human flow patterns around big cities (Shida et al. 2020). In contrast to the uncorrelated flow patterns in the afternoon, there are strong flows towards the city center from suburban areas in the morning, and inherent new universal laws of the human flows have been discovered which can be characterized and understood by the 3-dimensional structure of central city buildings and the fractal structure of main transport links. Here, we compare the results of the human flow pattern under the effect of COVID-19 pandemic with the analysis results in the 2015 data (Shida et al. 2020) before the spreading of COVID-19 pandemic.

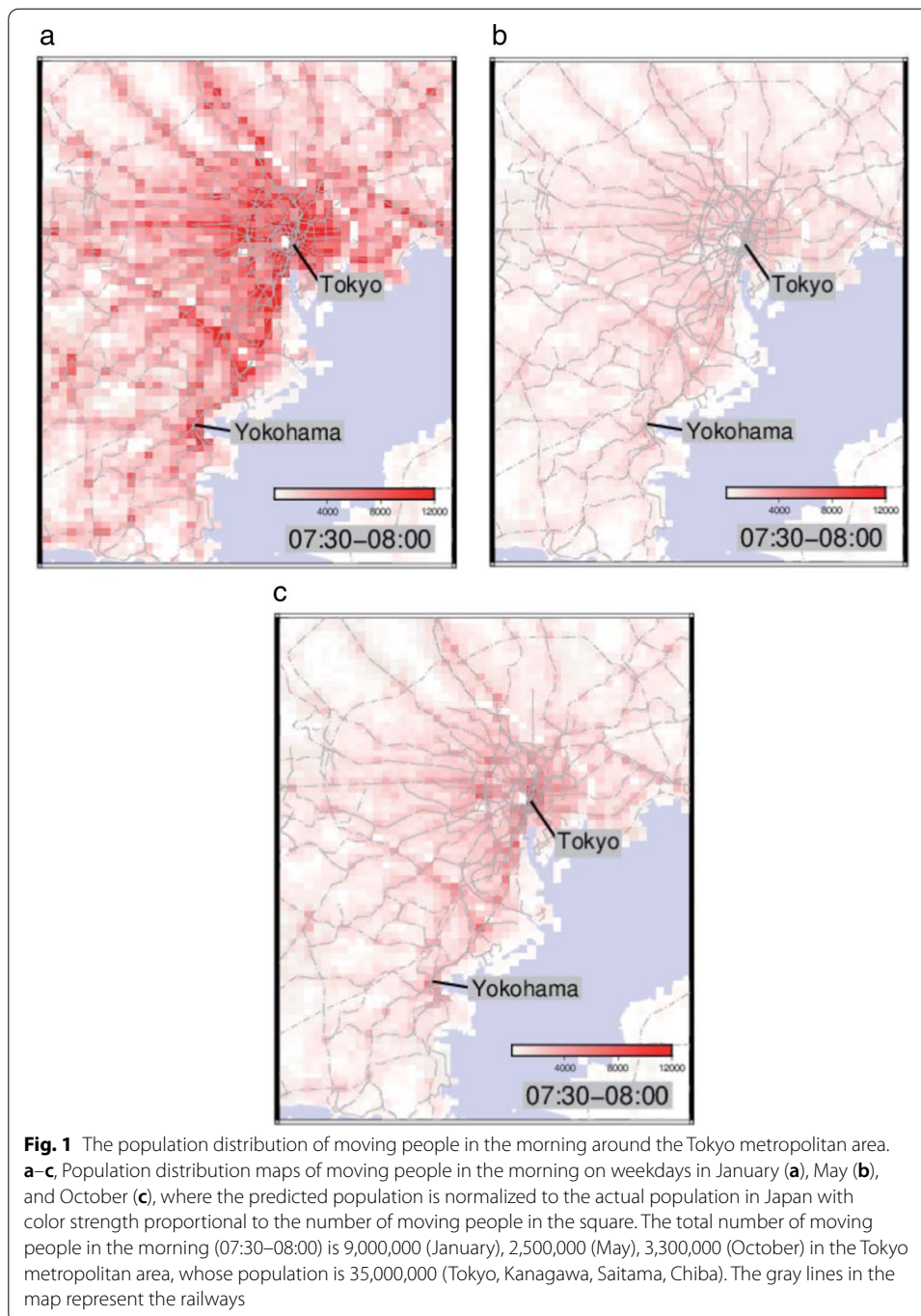
Results

The data

The GPS data was purchased from a Japanese private company <https://www.agoop.co.jp/en/>. We analyzed the data for all days in 2020. The data consist of user ID, time, latitude, longitude, speed, and direction. The number of users is about 1 million with intervals of data transmission mostly less than 10 min. For protection of privacy, the data transmission stops in the midnight and the user ID is re-newed every day.

The impact of emergency state issued in Japan

The declaration of emergency state issued in Japan for COVID-19 from April 7th to May 25th severely restricted the movement of people. In Fig. 1a–c, we show the monthly population distribution on weekdays of moving people in the morning (07:30–08:00) around the Tokyo metropolitan area, in three different months.



In contrast to the intense commuter rush in January, we can see that the number of moving people in May has decreased significantly. The population in each square has decreased by about 70% on average, indicating that many people chose telework. In October, the movement of people has revived a little. This is probably because some companies have canceled telework due to reasons such as business productivity and poor internal communication <https://www.tokyo-cci.or.jp/page.jsp?id=1023286>.

Drainage basin structures under the effect of COVID-19 pandemic

We apply the drainage basin analysis method that has been developed by us Shida et al. (2020) to characterize the human flow patterns during the COVID-19 pandemic, where the analysis range is from April 7 to June 30, 2020 on weekdays, after the state of emergency was announced. Our basin analysis is very simple (Shida et al. 2020). First, in Fig. 2a, b, we divide the map into squares of $500\text{ m} \times 500\text{ m}$ square in time intervals of 30 min (5:00–24:00) and calculate the mean velocity vector and the population of moving people in each square. Next, in analogy to river analysis (Shida et al. 2020), we perform the operation of connecting to one of the four adjacent sections according to the direction of the velocity vector of each square. This operation is applied to all squares, and the drainage basin cluster is uniquely determined.

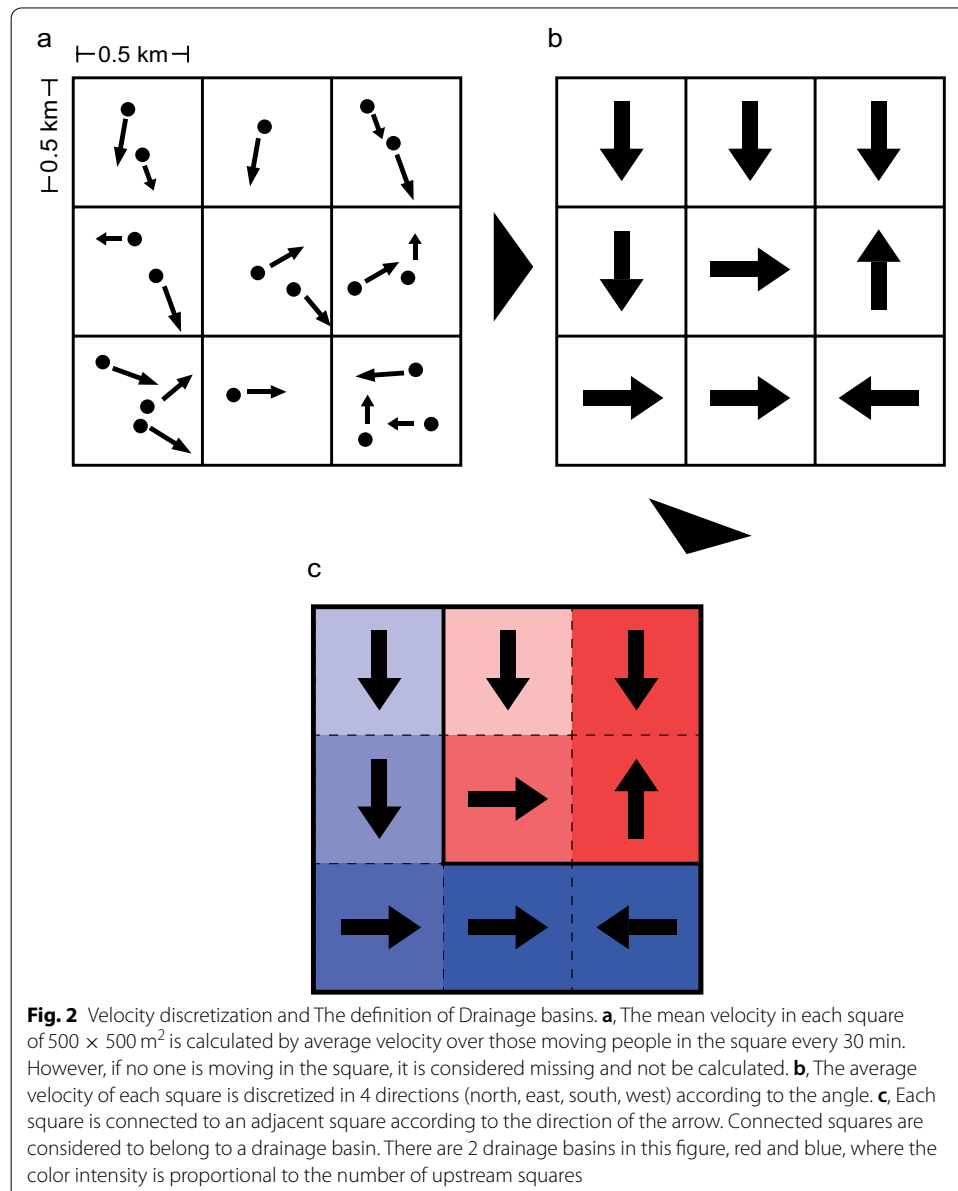


Figure 2c shows an example of creating a simple drainage basins. It is possible to divide the focusing area into each basin and further investigate its internal structure. By this operation, it is possible to divide the human flow into several basin clusters, and if there is a flow towards the city center, for example, a huge basin is expected to appear.

Figure 3a, b are top 15 basins drawn in the Tokyo metropolitan area in the morning and noon, where dark squares mean that they are located downstream in the basin. In the morning, we can see that huge basins appear around the center of Tokyo. The basins in the daytime are smaller than the morning basins. At first glance, the pattern of basins look similar to the random patterns observed before the spreading of COVID-19 pandemic, but we can see that the basins are more heading toward the center of Tokyo.

To understand these size differences, we apply the same drainage basin analysis for the nine metropolitan areas of Japan and focus on the size distribution. Figure 4a, b show the cumulative distribution function (CDF) in the morning and noon, respectively. The y-axis shows the cumulative distribution and the x-axis shows the basin size normalized by the mean basin size. The size distributions in the morning are straight lines on the log-log plot and can be approximated by a power law with an exponent value of about 2.4 which are similar to those found in normal times. It can be seen that the basin size distributions of Tokyo and Sapporo in the daytime deviate significantly from a straight line, which is very different from the simulation results (dotted lines). Tokyo and Sapporo took the most amount of time to lift their emergency declarations <https://www3.nhk.or.jp/nhkworld/en/news/backstories/1109/>, meaning that those cities most affected by COVID-19. The weak directed human flow in Tokyo and Sapporo, which is different from random in the daytime, is probably due to the staggered commuting hours to avoid the infection caused by congestion.

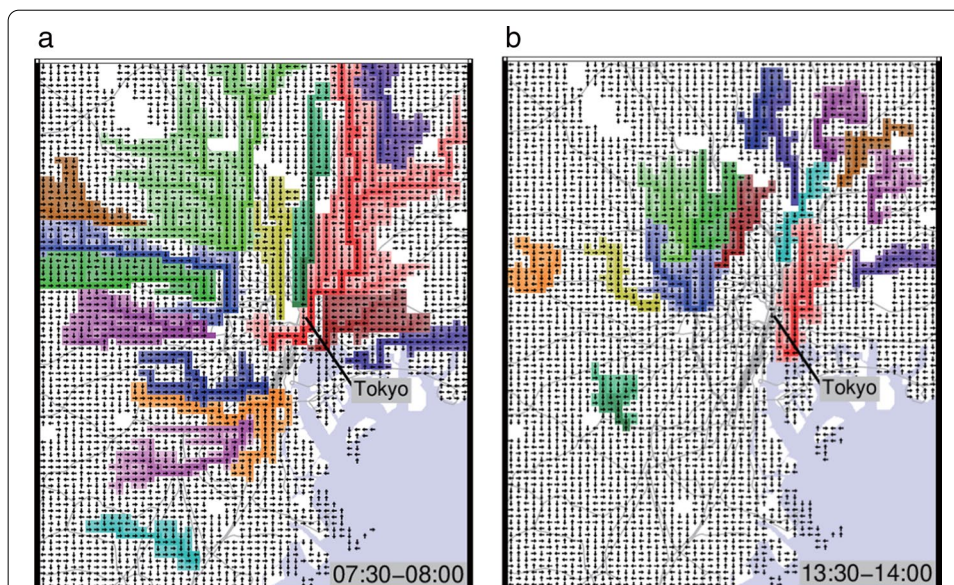
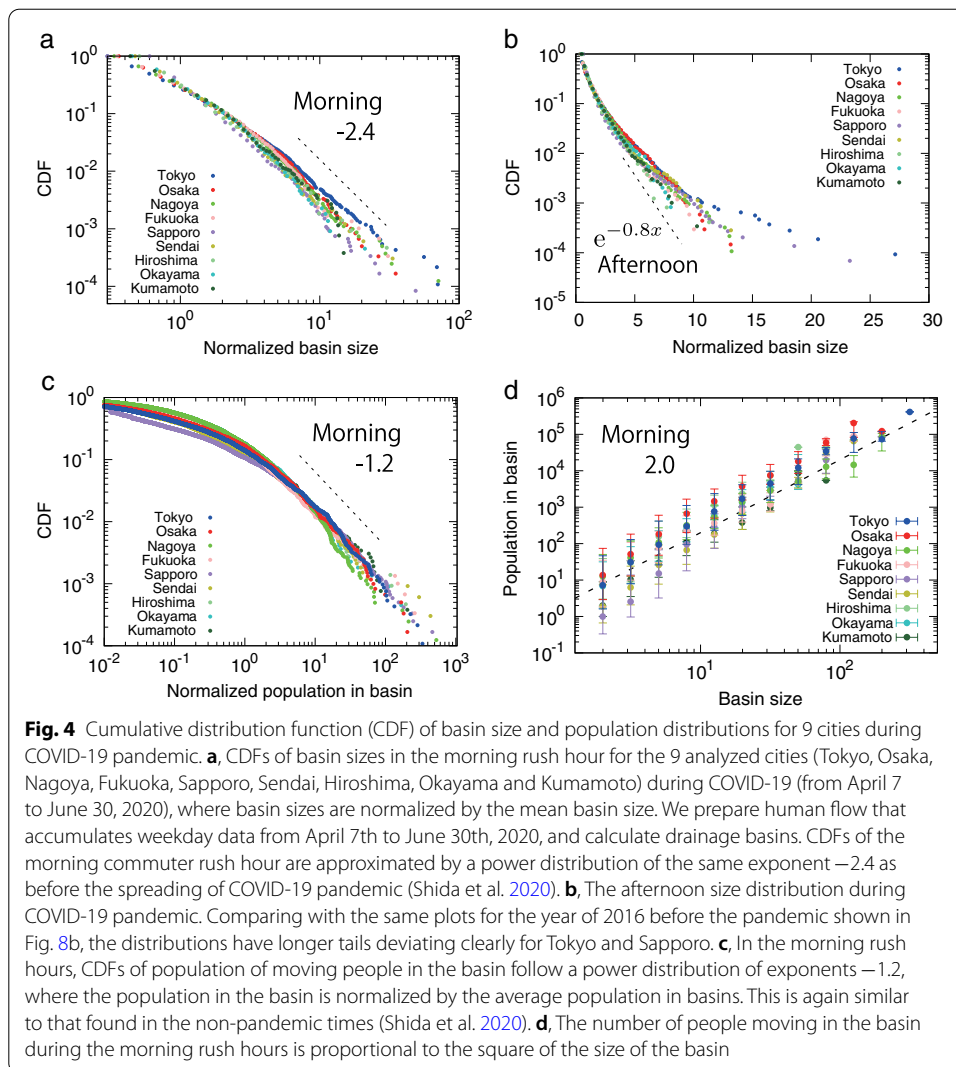


Fig. 3 Drainage basins around Tokyo metropolitan area during COVID-19 pandemic. **a–b**, Flow maps of basins in **a** the morning commuter rush hour (07:30–08:00) and **b** the afternoon (13:30–14:00) in the Tokyo metropolitan area, where the largest 15 basins are shown in different color codes. The display area is about 20×30 km. The analysis range is from April 7 to June 30, 2020



Next, we focus on the number of moving people in the basin during the morning hours. Figure 4c shows that the cumulative distributions of the number of moving people can be approximated by a power law with an exponent value close to 1.2. Figure 1 shows that the number of moving people has decreased significantly due to the COVID-19 pandemic, but surprisingly, the distributions of moving people in each basin have similar power law exponents as before the spreading of COVID-19 pandemic. This suggests that the reduced number of people in each grid is roughly the same fraction of (0.7) each grid. This indicates that the shrink of moving people was uniform, with almost the same fraction. From these power law exponents, the relationship between the size S_b and the number of moving people p_b in the b -th basin is given as:

$$p_b \propto S_b^2, \tag{1}$$

which is invariant although population density decreased. This relationship can be confirmed directly from Fig. 4d.

Fractal structures

Next, we calculate the diameter L_b of the basin, b , and confirm the universality of the structure of the basin. The diameter L_b is defined by the maximum distance between two points in each basin. Figure 5a indicates a size S_b is proportional to the diameter L_b to the power of 1.5. Using the fractal measure relations (Takayasu 1990), we can estimate the fractal dimension of the basin size. Since the size of the basin is considered to be closely related to the railway and road network, the fractal property does not change despite the significant decrease in the number of people in movement. Furthermore, in Fig.5b, the population of moving people in the basin p_b is also proportional to the diameter L_b cube, and the three-dimensionality of the city remains maintained. Since it takes many years and labor to change the structure of the city, it is reasonable that the three-dimensional structure of the city did not change during the COVID-19 pandemic. That is, the following relationship

$$L_b \propto p_b^{\frac{1}{3}} \propto S_b^{\frac{1}{1.5}}, \tag{2}$$

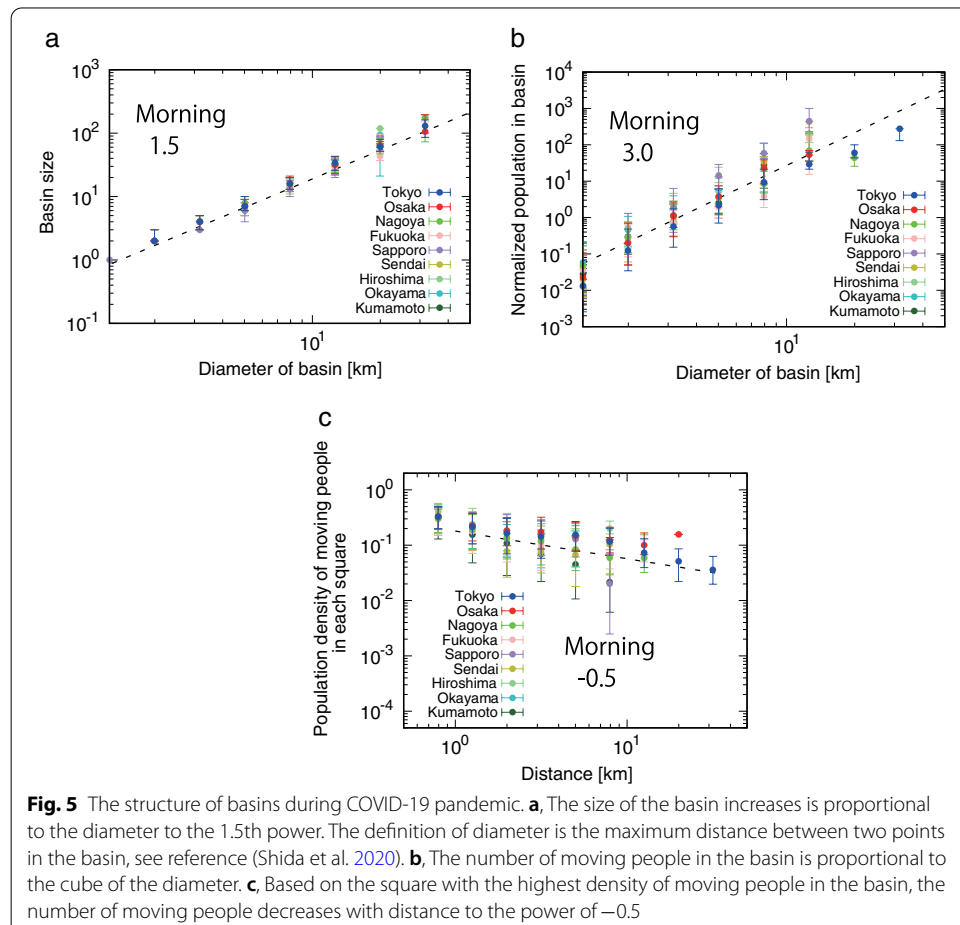
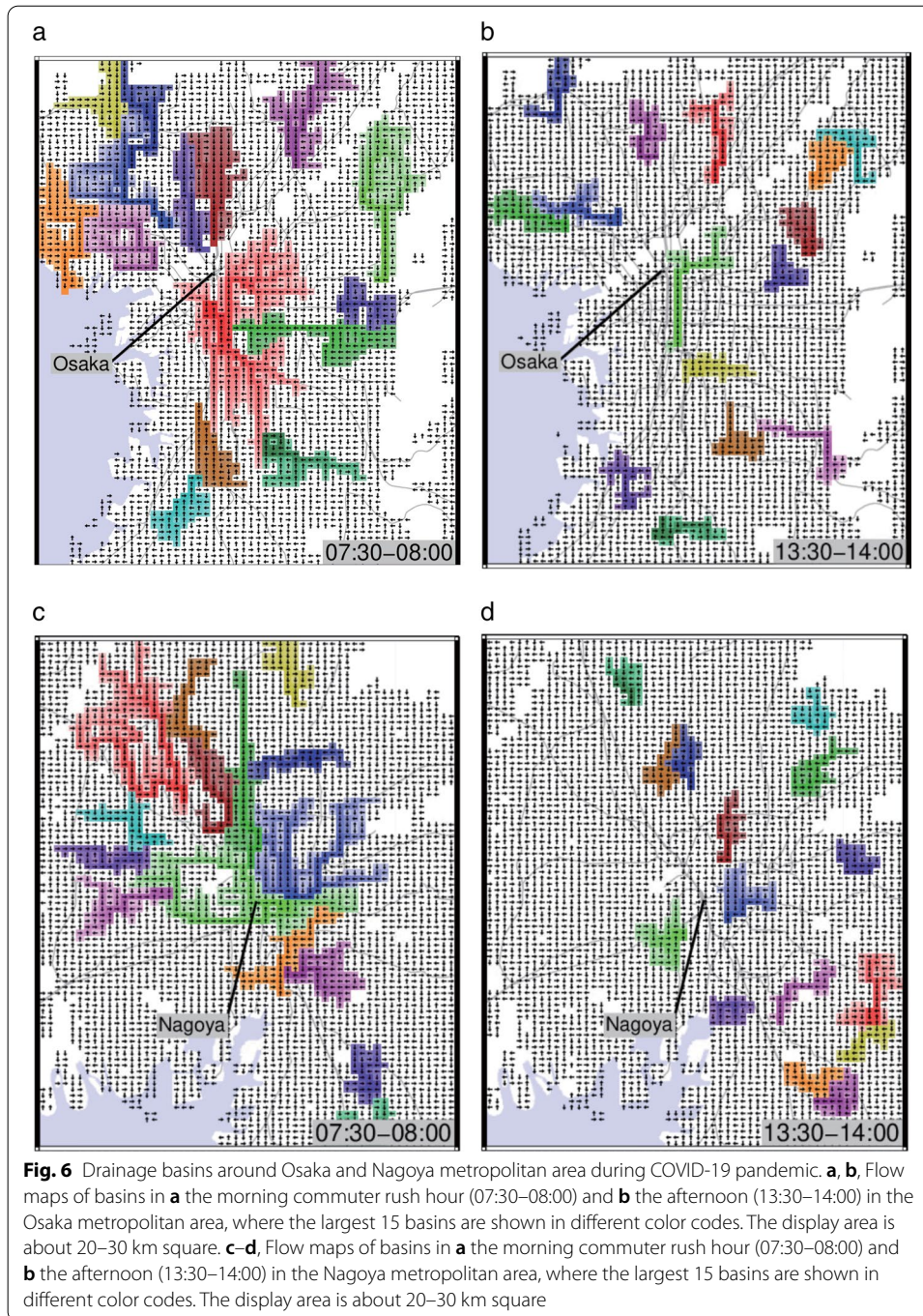
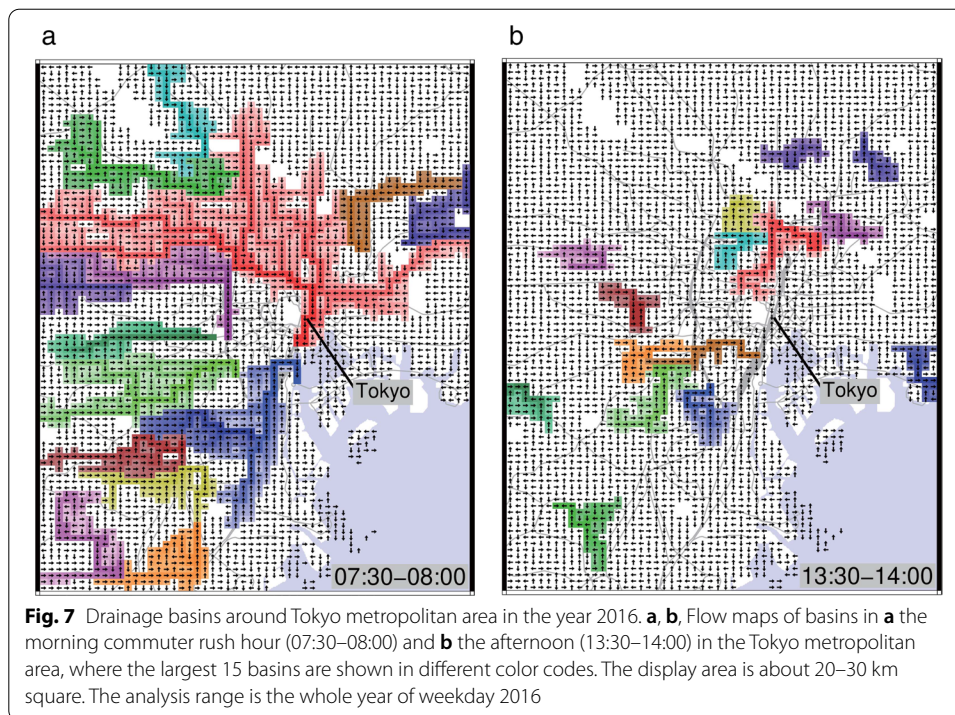


Fig. 5 The structure of basins during COVID-19 pandemic. **a**, The size of the basin increases is proportional to the diameter to the 1.5th power. The definition of diameter is the maximum distance between two points in the basin, see reference (Shida et al. 2020). **b**, The number of moving people in the basin is proportional to the cube of the diameter. **c**, Based on the square with the highest density of moving people in the basin, the number of moving people decreases with distance to the power of -0.5



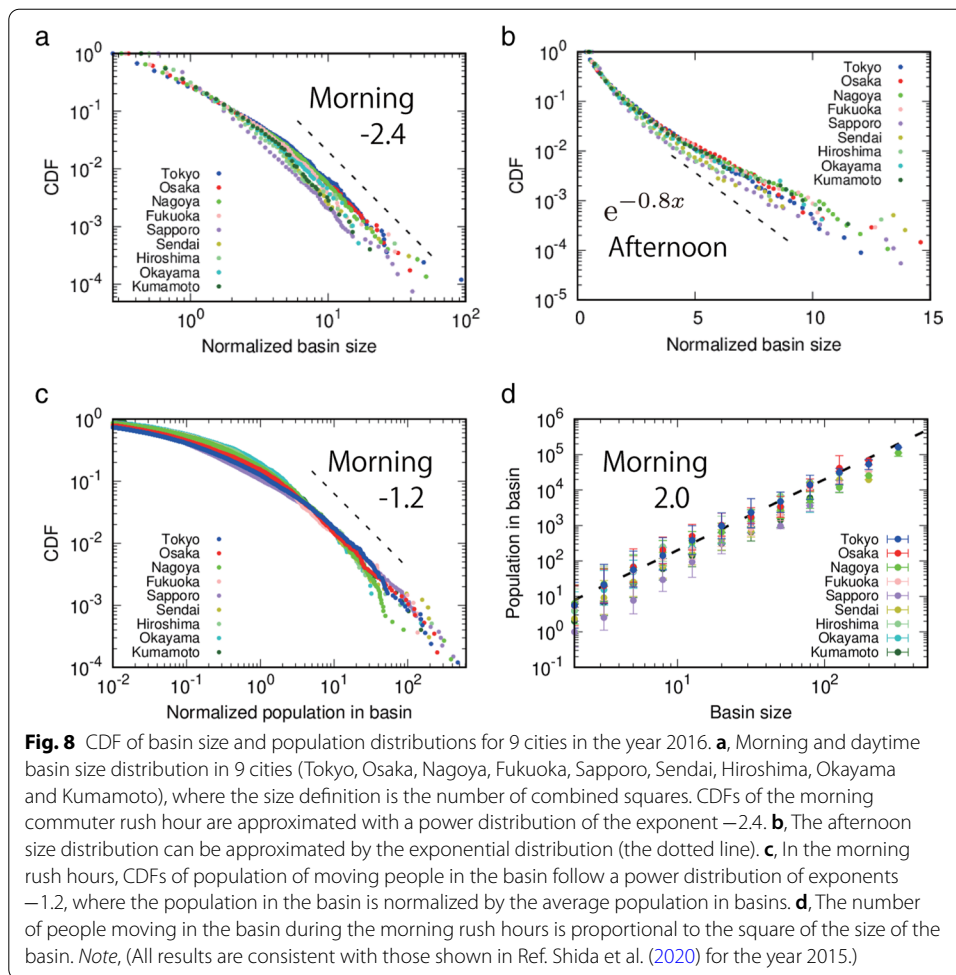
holds unchanged between the diameter L_b , size S_b , and population p_b of the basin, despite the significant reduction in the number of moving people to prevent the spread of infection. Finally, in Fig. 5c, we show the relation between population of moving people as a function of distance r from the most populated square to reveal the population



distribution in each basin. The population of moving people in each square is found to be inversely proportional to the square root of the distance r . This is the same exponent as found before the spreading of COVID-19 pandemic, meaning that the government's declaration of a state of emergency resulted in a uniform voluntary restraint regardless of the region.

Conclusion

In summary we analyzed the human flow patterns in 9 urban areas in Japan under the COVID-19 pandemic expansion based on the drainage basin analysis of GPS data. Before the pandemic the afternoon basin size distribution was approximated by an exponential distribution, which indicate random movements, however, the distribution of Tokyo and Sapporo deviates significantly from the exponential distribution in the period of government's declaration of a state of emergency caused by the COVID-19 pandemic. This deviation is probably caused by people's choice not to travel at peak time in order to avoid congestion. On the other hand, during the morning rush hour, the scaling laws hold universally, even though the number of moving people in the basin has decreased significantly. The fact that these scaling laws, which are closely related to the three-dimensionality of the city and the fractal structure of transportation links, have not changed is considered to indicate that the structure of the city has not changed in spite of movement restrictions conducted. Finally, considering the universality of population distribution within the basin may help prevent congestion. For example, if the arrival time is shifted according to the distance to the destination, the population



distribution of moving people in the basin is expected to change significantly. If it is possible to restrict movement for each individual based on GPS data, more efficient infection prevention measures may be possible.

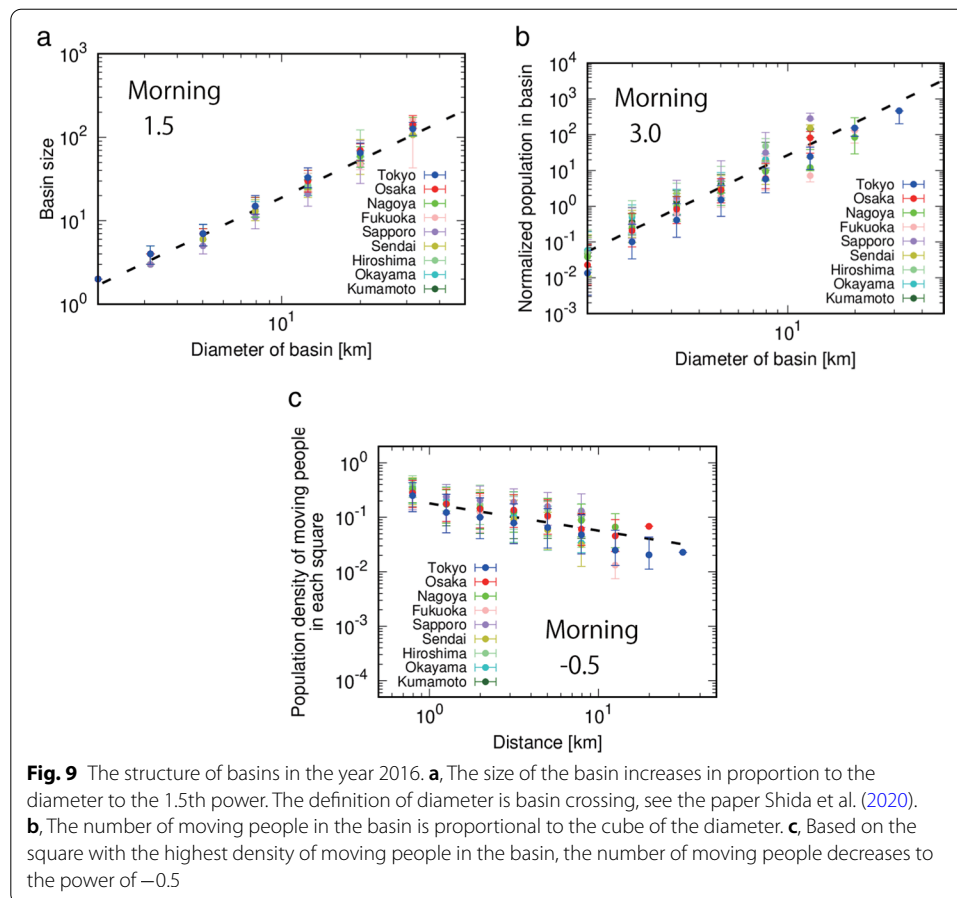
Appendix

Drainage basins around Osaka and Nagoya metropolitan area

Figure 6 show the top 15 basins drawn in the Osaka and Nagoya metropolitan area in the morning and noon.

Drainage basin structures in the year 2016 before the COVID-19 period

For comparison with Figs. 3, 4 and 5, here we show Figs. 7, 8 and 9 which are produced by the same procedures applied for the whole year 2016 before the COVID-19. All results are consistent with those in Ref. Shida et al. (2020) for the year 2015.



Abbreviations

GPS: Global positioning system; CDF: Cumulative distribution function.

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Authors' contributions

MT was the leader of this project, designed the whole research plan and directed writing of the manuscript. YS analyzed the raw data, performed the numerical calculations, and wrote the manuscript. HT and SH developed methods of data analysis and revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

Our data cannot be open to public, but the same data can be purchased from a Japanese private company, <https://www.agoop.co.jp/en/>, which sells "The location information big data which acquired from the smart phone app."

Declarations

Ethics approval and consent to participate

The GPS data we analyzed are anonymized and no personal information is included. Our analyses focus on macroscopic human flow patterns, so there is no need for informed consent.

Competing interests

The authors declare that they have no competing interests.

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