Influence of Absolute Humidity and Population Density on COVID-19 Spread and Decay Durations: Multi-prefecture Study in Japan

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Abstract
This study analyzed the spread and decay durations of the COVID-19 pandemic in different prefectures of Japan. In Japan, in addition to affordable wide coverage health insurance systems, no medical collapse was observed, making accurate comparisons between prefectures possible. For the 19 prefectures included in this study that had daily maximum confirmed cases exceeding ten, the confirmed cases increased and decreased exponentially in the spread and decay durations in most of the prefectures. A good correlation was observed between the spread and decay durations ($R^2=0.37$). However, some exceptions were observed in prefectures that are adjacent to primary prefectures (e.g., Tokyo, Osaka, Aichi, and Fukuoka) and in areas where people returned from foreign countries, which were defined origins of cluster infections. Excluding these prefectures, population density is shown to be the primary factor affecting spread and decay patterns, with correlations of 0.52 and 0.76, respectively. The absolute humidity also affected the spread duration ($R^2=0.40$). These findings could be useful for intervention planning during potential future pandemics, including a second COVID-19 outbreak.

Introduction

The coronavirus infectious disease of 2019 (COVID-19) outbreak has been reported worldwide (Wu and McGoogan, 2020; World Health Organization, 2020). An extensive number of studies on COVID-19 have been conducted from varying aspects, including prevention, control, diagnosis, causes, and epidemiology (Adhikari et al., 2020). In Japan, a state of emergency was declared in 7 out of 47 prefectures on April 7, 2020, lifted nationwide on April 16, and called off on May 25, 2020. During this state of emergency, people voluntarily
self-contained instead of a government-enforced lockdown of the prefectures.

Many epidemic modeling papers have been proposed (Hethcote, 2000; Daley and Gani, 2001; Keeling and Rohani, 2011) and for COVID-19, various mathematical models have been presented for different purposes, such as serial intervals (Nishiura et al., 2020) and case studies in Wuhan (Lin et al., 2020) and Italy (Giordano et al., 2020). Comparisons with different countries have also been made (Reis et al., 2020) and their importance in the developing policies has been discussed by Currie et al. (2020).

The epidemic duration and morbidity rates of COVID-19 are not easy to compare because of the different co-factors affecting them. The number of polymerase chain reaction (PCR) tests, which is a simple and cost-effective testing method, is limited in Japan due to its reliability; therefore, a chest CT was performed to obtain a highly accurate diagnosis (Ai et al., 2020). In addition, to avoid nosocomial infections and medical resource shortages, it was suggested that people with symptoms (e.g., fever > 37.5°C) for no more than four consecutive days) stay home and not seek medical attention, but only in cases where there was no close contact with infected people or no record of visiting foreign countries. Some patients have been reported to be asymptomatic (Repici et al., 2020), making the study of COVID-19 more complex.

The statistics of confirmed deaths and positive patients have been updated every day in each prefecture of Japan. In Japan, there has been no reported medical system collapse and due to the health insurance system, COVID-19 medical care is offered for free. However, the percentage of positive test cases differ by an average factor of 3 and range from 2.2-34.8% (see Table 1) throughout Japan, making morbidity estimations in different areas more difficult.

Co-factors potentially influencing COVID-19 morbidity including ambient temperature, absolute humidity, air pollution, etc. were studied (Ma et al., 2020; Wang et al., 2020; Tosepu et al., 2020; Ogen, 2020; Zhu and Xie, 2020; Liu et al., 2020; Tomar and Gupta, 2020). However, these studies, as well as the above-mentioned modeling studies, do not consider the impact of population density and ambient conditions on the spread and decay durations (Oliveiros et al., 2020). The necessity of population density scaling has been suggested for infectious diseases (Hu et al., 2013) and factors characterizing the spread and decay durations might be different.

The purpose of this study is to evaluate the effect of different external factors on the pattern of spread and decay durations of the epidemic in different Japan prefectures.
Data and Processing

Three datasets were utilized in this study. The first dataset is the number of confirmed positive cases in each prefecture, which was obtained from Toyo Keizai Online (2020) and is based on a report by the Ministry of Health, Labour and Welfare (Ministry of Health Labour and Welfare, 2020). Because the state of emergency was terminated on May 25, 2020, this study utilized time-course data from March 15, 2020 until that date. COVID-19 started

Table 1. Population, area, and population density of 19 prefectures where daily maximum cases of COVID-19 exceeded 10. Total cases of COVID-19 and mean percentage of the positive test cases are also listed

| Prefecture | Population (thousand persons) | Population density (people per km²) | Total Cases through May 25 | Daily Max Cases | Percentage of Positive Test Results (%) |
|------------|-------------------------------|-------------------------------------|---------------------------|-----------------|-----------------------------------------|
| Tokyo      | 13,921                        | 6,354.8                             | 5,170                     | 206             | 34.8                                    |
| Kanagawa*  | 9,198                         | 3,807.5                             | 1,356                     | 94              | 14.7                                    |
| Saitama*   | 7,350                         | 1,932.0                             | 1,000                     | 56              | 5.2                                     |
| Chiba*     | 6,259                         | 1,217.4                             | 904                       | 70              | 6.4                                     |
| Ibaraki    | 2,860                         | 470.4                               | 168                       | 28              | 3.7                                     |
| Gunma      | 1,942                         | 304.6                               | 149                       | 44              | 4.2                                     |
| Shizuoka   | 3,644                         | 467.9                               | 75                        | 18              | 2.2                                     |
| Aichi      | 7,552                         | 1,460.0                             | 507                       | 21              | 5.2                                     |
| Gifu**     | 1,987                         | 187.3                               | 150                       | 18              | 4.4                                     |
| Ishikawa   | 1,138                         | 271.7                               | 296                       | 20              | 11.2                                    |
| Toyama     | 1,044                         | 245.6                               | 227                       | 21              | 7.3                                     |
| Osaka      | 8,809                         | 4,631.0                             | 1,781                     | 108             | 6.1                                     |
| Hyogo***   | 5,466                         | 650.4                               | 699                       | 57              | 6.4                                     |
| Kyoto***   | 2,583                         | 560.1                               | 358                       | 20              | 4.6                                     |
| Shiga***   | 1,414                         | 352.0                               | 100                       | 12              | 5.7                                     |
| Hiroshima  | 2,804                         | 331.1                               | 167                       | 51              | 2.5                                     |
| Fukuoka    | 5,104                         | 1,024.8                             | 672                       | 108             | 5.7                                     |
| Saga****   | 815                            | 333.6                               | 47                        | 11              | 3.4                                     |
| Okinawa    | 1,453                         | 637.5                               | 81                        | 17              | 2.9                                     |

*Kanagawa, Saitama, and Chiba were considered adjacent prefectures of Tokyo.

**Gifu was considered an adjacent prefecture of Aichi.

***Hyogo, Kyoto, and Shiga were considered adjacent prefectures of Osaka.

****Saga was considered an adjacent prefecture of Fukuoka.
spreading in mid-February in the Aichi prefecture, which is the only location where spread started earlier than March 15. As such, additional data were obtained from the Aichi prefecture website (Aichi Prefecture, 2020) to include the earlier data when the spread started.

![Diagram](image)

Fig. 1. Definition of the spreading and converging duration during the COVID-19 pandemic, which has been applied to the 7-day moving average value data. Time parameters extracted from the definition are $T_{SS}$ (start of spread), $T_{SE}$ (end of spread), $T_{DS}$ (start of decay), $T_{DE}$ (end of decay), $D_S$ (spread duration), and $D_D$ (decay duration).

The number of confirmed positives may be influenced by the diagnostic data due to Japanese guidelines, serial intervals, and latency, which is affected by the doctor’s judgment; therefore, the moving average over 7 days ($\pm 3$ days in addition to the corresponding day) was considered to reduce the effect of potential singularities. Additional small peaks were still observed, which is attributable to the cluster of patients (e.g., nosocomial infections, nursing home patients, and people returning from foreign countries).

This tendency prevents the direct fitting of the measured results of a comparison with a computational model (typically expressed with an exponential trend (Ceylan, 2020)). Therefore, this study introduced the criteria of days required for spreading from 10% to 90% and decaying from 90% to 10% of the peak of the confirmed positives (7-day average), as metrics for evaluation, as shown in Fig. 1. A limitation of this metric is that a certain minimum number of samples are needed, because if the number of samples is small, one or two new patients would significantly influence the results. Therefore, as a pre-processing step, prefecture data was excluded if the daily maximum number of confirmed positive cases was
less than 10. Based on this criterion, 19 prefectures met the minimum confirmed positive cases.

Table 2. Starting and terminating dates of the spread and decay stages of COVID-19 pandemic and the date when the daily peak value of confirmed cases was reported.

| Prefecture | $T_{SS}$ | $T_{SE}$ | Daily peak* | $T_{DS}$ | $T_{DE}$ | $D_s$ | $D_o$ |
|------------|----------|----------|-------------|----------|----------|-------|-------|
| Tokyo      | 17-Mar   | 3-Apr    | 17-Apr      | 10-Apr   | 7-May    | 17    | 27    |
| Kanagawa   | 19-Mar   | 3-Apr    | 10-Apr      | 11-Apr   | 19-May   | 15    | 38    |
| Saitama    | 17-Mar   | 5-Apr    | 10-Apr      | 13-Apr   | 6-May    | 19    | 23    |
| Chiba      | 19-Mar   | 2-Apr    | 17-Apr      | 13-Apr   | 5-May    | 14    | 22    |
| Ibaraki    | 16-Mar   | 28-Mar   | 3-Apr       | 8-Apr    | 23-Apr   | 12    | 15    |
| Gunma      | 25-Mar   | 5-Apr    | 11-Apr      | 9-Apr    | 22-Apr   | 11    | 13    |
| Shizuoka   | 25-Mar   | 3-Apr    | 10-Apr      | 6-Apr    | 27-Apr   | 9     | 21    |
| Aichi      | 22-Feb   | 30-Mar   | 4-Apr       | 1-Apr    | 27-Apr   | 37    | 26    |
| Gifu       | 25-Mar   | 4-Apr    | 8-Apr       | 6-Apr    | 17-Apr   | 10    | 11    |
| Ishikawa   | 24-Mar   | 3-Apr    | 20-Apr      | 8-Apr    | 8-May    | 10    | 30    |
| Toyama     | 1-Apr    | 13-Apr   | 17-Apr      | 18-Apr   | 30-Apr   | 12    | 12    |
| Osaka      | 18-Mar   | 6-Apr    | 14-Apr      | 13-Apr   | 6-May    | 19    | 23    |
| Hyogo      | 19-Mar   | 4-Apr    | 9-Apr       | 7-Apr    | 4-May    | 16    | 27    |
| Kyoto      | 16-Mar   | 2-Apr    | 7-Apr       | 5-Apr    | 9-May    | 17    | 34    |
| Shiga      | 25-Mar   | 4-Apr    | 16-Apr      | 15-Apr   | 22-Apr   | 10    | 7     |
| Hiroshima  | 26-Mar   | 6-Apr    | 12-Apr      | 10-Apr   | 27-Apr   | 11    | 17    |
| Fukuoka    | 22-Mar   | 1-Apr    | 11-Apr      | 9-Apr    | 27-Apr   | 10    | 18    |
| Saga       | 23-Mar   | 15-Apr   | 19-Apr      | 22-Apr   | 1-May    | 23    | 9     |
| Okinawa    | 28-Mar   | 3-Apr    | 7-Apr       | 10-Apr   | 25-Apr   | 6     | 15    |

*Moving average is not applicable for daily peak values.

The second dataset consists of population and prefecture area, which were obtained from the Statistics Bureau of Japan (2020) (Table 1). Several prefectures were classified as geographically adjacent to primary prefectures (Tokyo, Osaka, Aichi, and Fukuoka; Table 1). In adjacent prefectures, a number of people were found to commute to the primary prefectures, thus potentially affecting the prefecture data, which may not be neglected.

The third dataset was weather data that was obtained from the Japan Meteorological Agency for each prefecture during the time period of the pandemic. The absolute humidity was derived from the relative humidity and ambient temperature data (Japan Meteorological
Fig. 2. (a) Spread and (b) decay durations (days) of 19 prefectures in Japan. Dashed lines represent the prefectures that are adjacent to primary prefectures (Tokyo, Osaka, Aichi, and Fukuoka).
Fig. 3. Relationship between the periods of spread and convergence. The triangle markers represent prefectures close to the primary prefectures (Tokyo, Osaka, Aichi, and Fukuoka).

Fig. 4. Relationship of the spread and decay durations ($D_S$ and $D_D$) with population density. (a) and (b) represent the total 19 prefectures while (c) and (d) are for prefectures excluding the adjacent ones.
**Results**

Table 2 lists the starting and terminating dates of the spread and decay stage (using moving averages) and indicates the date when the daily peak values (without averaging) of cases was observed for each prefecture. Figure 2 shows the time course of the confirmed new positive cases for the spread and decay periods based on the data in Table 2.

As shown in Fig. 2(a), the number of normalized confirmed cases increased exponentially in most prefectures and multiple peaks were observed in some prefectures. In Aichi, the start of the spread period, $T_{SS}$, was three weeks earlier than the other studied prefectures (Table 2), and in mid-March, due to the Japanese requirement, the travelling residents returned home from foreign countries, resulting in two large peaks in the spread period. A similar tendency was observed in Saga. In Chiba, Shiga, and Gifu only small peaks were observed.

As shown in Fig. 2(b), the number of normalized confirmed cases decreased exponentially in most prefectures. Similar to Fig. 2(a), multiple peaks were observed in some prefectures including Kanagawa and Hyogo. In Ishikawa, the second peak, which is approximately 0.9, occurred on April 17, 2020 and was caused by travelers returning from foreign countries (Ishikawa Prefecture, 2020). The same curve pattern was observed in Aichi.

Figure 3 shows the relationship between the duration of the spread and decay periods. A good correlation was observed between these two periods, especially for prefectures that were not classified as adjacent prefectures. In addition, the plots of Aichi and Ishikawa, whose curves include multiple peaks, are outside the regression lines.
Table 3. Daily average, maximum temperature, absolute humidity, and diurnal range in temperature or absolute humidity. These values are averaged during the spread and decay stages as listed in Table 2.

|        | $T_{\text{ave}}$ | $T_{\text{max}}$ | $T_{\text{diff}}$ | $H_{\text{ave}}$ | $H_{\text{max}}$ | $H_{\text{diff}}$ | $T_{\text{ave}}$ | $T_{\text{max}}$ | $T_{\text{diff}}$ | $H_{\text{ave}}$ | $H_{\text{max}}$ | $H_{\text{diff}}$ |
|--------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Tokyo  | 11.9             | 16.6             | 9.5              | 6.4              | 9.1              | 4.4              | 14.4             | 18.8             | 8.6              | 8.6              | 10.4             | 3.4              |
| Kanagawa | 12.4            | 16.3             | 8.2              | 6.8              | 9.6              | 4.8              | 16.6             | 20.4             | 7.2              | 9.8              | 11.5             | 3.7              |
| Saitama | 11.1             | 16.5             | 11.2             | —                | —                | —                | 14.6             | 19.4             | 9.4              | —                | —                | —                |
| Chiba  | 12.4             | 15.9             | 7.7              | 6.6              | 9.4              | 4.7              | 15.1             | 18.8             | 7.3              | 8.4              | 10.2             | 3.5              |
| Ibaraki | 10.3            | 16.8             | 13.0             | 5.7              | 8.4              | 4.6              | 10.8             | 15.1             | 8.5              | 6.5              | 8.0              | 3.0              |
| Gunma  | 10.6             | 15.1             | 9.5              | 5.7              | 7.3              | 2.8              | 11.5             | 16.0             | 8.6              | 6.3              | 9.5              | 3.5              |
| Shizuoka | 13.1            | 16.6             | 7.3              | 8.6              | 10.6             | 4.0              | 14.3             | 18.7             | 8.7              | 7.1              | 8.9              | 3.6              |
| Aichi  | 10.1             | 14.6             | 8.3              | 5.9              | 7.7              | 3.3              | 13.0             | 17.7             | 8.9              | 6.5              | 8.2              | 3.2              |
| Gifu   | 12.0             | 16.2             | 8.2              | 6.7              | 8.3              | 3.3              | 12.6             | 17.9             | 9.9              | 5.1              | 6.5              | 2.7              |
| Ishikawa | 9.9             | 13.7             | 7.8              | 5.9              | 7.2              | 2.8              | 13.1             | 17.0             | 7.6              | 7.0              | 8.6              | 3.0              |
| Toyama | 9.7              | 14.2             | 8.7              | 6.3              | 7.5              | 2.6              | 12.1             | 17.3             | 9.4              | 7.5              | 8.9              | 2.9              |
| Osaka  | 12.8             | 16.6             | 7.5              | 6.7              | 8.9              | 3.7              | 16.2             | 20.3             | 7.9              | 7.4              | 9.0              | 3.0              |
| Hyogo  | 13.1             | 16.5             | 6.8              | 7.3              | 9.6              | 4.0              | 14.8             | 17.9             | 6.1              | 7.8              | 9.3              | 3.1              |
| Kyoto  | 11.5             | 16.2             | 9.2              | 6.4              | 8.6              | 3.7              | 14.7             | 19.8             | 9.5              | 7.1              | 8.9              | 3.4              |
| Shiga  | 11.1             | 15.4             | 8.6              | —                | —                | —                | 12.9             | 17.2             | 8.7              | —                | —                | —                |
| Hiroshima | 12.4           | 16.2             | 7.6              | 6.5              | 8.5              | 3.5              | 13.2             | 17.4             | 8.2              | 5.6              | 7.4              | 3.2              |
| Fukuoka | 14.2            | 17.3             | 5.8              | 8.8              | 10.8             | 3.8              | 14.0             | 17.1             | 6.0              | 7.3              | 9.3              | 3.4              |
| Saga   | 13.4             | 17.9             | 8.8              | 7.3              | 9.1              | 3.6              | 14.9             | 20.1             | 10.3             | 7.1              | 8.6              | 3.1              |
| Okinawa | 21.3            | 23.6             | 4.7              | 14.6             | 17.1             | 5.9              | 19.8             | 21.9             | 4.2              | 11.8             | 13.9             | 3.7              |

Figure 4 shows the relationship between the spread and decay durations ($D_S$ and $D_D$) with the population density for the 19 prefectures and for the prefectures excluding the adjacent prefectures as well as the resultant curves displayed multiple obvious peaks. As demonstrated in Fig. 4, the correlation between the spread and decay durations with the population was confirmed, and a better correlation was obtained by excluding the adjacent prefectures. The coefficients of determination in the spread stage for the 19 prefectures and for the prefectures excluding the adjacent prefectures were 0.163 and 0.521, respectively, and 0.336 and 0.768, respectively, in the decay stage.
The mean daily temperatures and humidity listed in Table 3 were obtained for the corresponding durations ($D_s$ and $D_d$) by prefecture as determined in Table 2. Fig. 5 shows the effect of the ambient parameters on the spread and decay durations. The daily mean, maximum, and diurnal change values were selected based on previous influenza studies (Park et al., 2019; Metz and Finn, 2015), which suggested that temperature variation and humidity are correlated with the COVID-19 mortality rate (Ma et al., 2020). As seen in Fig. 5, this
correlation was observed for the data utilized in this study. If the adjacent prefectures and those prefectures having multiple peaks in the curves are excluded, modest correlation is observed for average temperature and absolute humidity in the spread stage, and a marginal correlation is observed in the decay stage.

A multi-variant correlation study was conducted considering the average absolute humidity measured during the study period (pandemic spread and decay) and population density. The results yielded low $R^2$ values of 0.19 and 0.23 in the spread and decay stages, respectively, which demonstrates variability within some prefectures. Therefore, additional constraints were defined to exclude prefectures located adjacent to primary prefectures to avoid the influence of infections caused by neighboring major pandemic clusters. A set of nine prefectures demonstrated a high consistency with the average absolute humidity and population density, yielding $R^2$ values of 0.9 and 0.75 in the spread and decay stages, respectively. These results are presented in Fig. 6. This demonstrate a highly accurate spreading period can be estimated from population density and absolute humidity for prefectures satisfy some criteria (e.g. non-adjust to primary prefecture).

Fig. 6. Multi-variate regression (average humidity and population density) results considering 17 prefectures and selected 9 prefectures considering the days required for spread (top) and decay (bottom).
**Discussion and conclusion**

In this study, the COVID-19 spread and decay durations of 19 different prefectures in Japan that had daily maximum confirmed positive cases exceeded 10 were compared. The definition of the metrics for both durations from 0.1 to 0.9 of the normalized confirmed cases (Gusev et al., 2016) was introduced. Normalization was used to avoid potential differences in absolute number of cases reported among prefectures due to different regulations. The top and bottom 10% were excluded to avoid potential noise and extended tail effects.

Based on the results of this study, the number of confirmed cases generally increased and decreased exponentially; however, significant dual peaks were observed in Aichi and Saga in the spread stage and in Aichi and Ishikawa in the decay stage. In addition, small peaks were observed in the prefectures adjacent to the primary prefectures. In adjacent prefectures, the influence of the primary prefectures may not be neglected because residents commuting between prefectures influence the spread and/or decay durations. In the primary prefectures (except for Aichi), good correlations between spread and decay durations were observed.

This study evaluated the effect of population density as a rough surrogate of social distancing and ambient conditions during the identified durations. Based on the results of the study, it was determined that population density is a good metric to estimate duration, especially in the decay stage. This may implicitly support the importance of social distancing, which could be the edict in some countries (The Prime Minister in Action, 2020). Regarding ambient condition parameters, absolute humidity has the greatest effect in the spread stage; however, it is not significant in the decay stage. The importance of absolute humidity is suggested in a previous study on the influenza virus (Peci et al., 2019; Shimmei et al., 2020). An interesting point to be highlighted is that ambient conditions do not significantly influence the decay stage.

In conclusion, correlations between absolute humidity and population density were observed in the spread and decay stages of COVID-19. For a potential pandemic, especially a potential second wave of COVID-19, this factor should be considered as well as the multi-city comparison.
The relationship between the different ambient condition metrics and morbidity is often discussed (e.g., Kodera et al. (2019)). For the COVID-19 duration analyzed in this study, the correlation between maximum temperature and maximum absolute humidity in the spread duration presented in Fig. A1 shows a strong correlation ($R^2=0.92$, $0.67$). The duration of COVID-19 was generally limited to two months; thus, the metrics considered in the discussion of Fig. 6 are correlated, unlike the discussion of their annual impact on influenza (e.g., Shimmei et al. (2020)).

Fig. A1. Correlation of average temperature and absolute humidity in prefectures and time frame under study
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