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COVID-19 infection in Hokkaido, Japan might depend on the viscosity of atmospheric air

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ABSTRACT

Background: The large number of people infected with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has plunged the world into fear in recent times. In Japan, 18,769 novel coronavirus disease 2019 (COVID-19) cases have been reported as of June 30, 2020. This study aimed to assess whether cluster infection prevention is possible by evaluating the association between viral transmission and meteorological factors.

Methods: This study included 1263 people who were successively diagnosed with COVID-19 in Hokkaido, Japan between January 24, 2020 and June 30, 2020. After obtaining the values from the Japanese Meteorological Agency, the average scores of air temperature and humidity were calculated and compared with COVID-19 reproduction numbers, and the association between COVID-19 incidence or reproduction number and meteorological factors was assessed.

Results: The COVID-19 reproduction number in Hokkaido had three peaks that came several days before the surge in COVID-19 cases. The peaks are indicative of cluster infections. There was a strong negative correlation between the kinematic viscosity of atmospheric air and the reproduction number.

Discussion and Conclusion: Analysis of the reproduction number is important for predicting or suppressing COVID-19 infection clusters. The authors found a strong association between meteorological factors, such as kinematic viscosity of atmospheric air and the incidence of COVID-19 infection. Meteorological forecasts could provide foreknowledge about COVID-19 infection clusters in the future.

1. Introduction

The novel coronavirus disease (COVID-19) which is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has been spreading across the world. The economic damage due to long-term lockdowns imposed to contain the pandemic has been immeasurable. Meanwhile, every country has been struggling to curb the spread of the virus, and while some positive results have been seen recently, the outbreak continues to smolder in many countries and is only at the beginning stages of the pandemic in others. Various research organizations worldwide have been studying the characteristics of SARS-CoV-2; however, the virus remains poorly understood.

In Japan, there were 18,769 infected people as of June 30, 2020. The country consists of four main islands and a large number of small ones. Hokkaido covers an area of about 83,457 square kilometers and has a population of approximately 5.4416 million people. The island has one

of the highest incidences of COVID-19 infections in Japan, with the number of cases at 1263 (one-fifth of Tokyo's cases) as of June 30, 2020. The population density is 66 people per km, which is one-ninetieth of that of Tokyo. The COVID-19 infection clusters in Hokkaido indicate that the infection rate is not proportional to the population distribution.

It was reported that the outbreak of SARS in Guangdong, China in 2003 gradually diminished as the weather became warmer and ended by July, indicating that temperature variations might have affected the outbreak (Tan et al., 2005; Wallis and Nerlich, 2005). Moreover, humidity has also been found to be significantly correlated with viral survival and transmission rates (Pinheiro et al., 2014). COVID-19, which is similar to SARS but caused by a different coronavirus, was first reported in China (Wu et al., 2020). Some studies have reported that COVID-19 transmission is related to meteorological factors (Wang et al., 2020). In addition, many reports have demonstrated that the spread of contaminants is associated with meteorological factors (Bolano-Ortiz

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et al., 2020; Dbouk and Drikakis, 2020; Fareed et al., 2020; Meo et al., 2020a, b; Ogaugwu et al., 2020; Poirier et al., 2020; Sarkodie and Owusu, 2020). However, there are few reports discussing air viscosity, which could affect the spread area of contaminants, including viruses. We analyzed the correlation between COVID-19 incidence and meteorological factors, including air viscosity as it could affect the spread of droplets in the air (Reid et al., 2018).

Hokkaido, which is located in the northern part of Japan, has a large mountain range at its center. The island can be divided into five main areas: (1) Sea of Japan coast, (2) Inland, (3) Sea of Okhotsk coast, (4) Eastern Pacific, and (5) Western Pacific. The weather conditions, such as the air temperature, humidity, and daylight hours, are completely different in each area. While COVID-19 transmission may be affected by multiple factors, using reproduction number, this study explored the effects of three meteorological parameters (air temperature, humidity, and air viscosity) on the spread of the disease.

2. Materials and methods

2.1. Subjects

This study included 1263 people who were successively diagnosed with COVID-19 through polymerase chain reaction (PCR) testing in Hokkaido between January 24, 2020 and June 30, 2020. All data, including age, sex, residential area, information of close contact with an infected person, and onset date of symptoms, were obtained from the Japanese Ministry of Health, Labour and Welfare database (<http://www.mhlw.go.jp/english/>). Meteorological data were obtained from the Japanese Meteorological Agency (<https://www.jma.go.jp/jma/indexe.html>).

As it is difficult to accurately identify the infection date, it was presumed to be 6–8 days (average 7 days) before the onset of a patient's symptoms, based on the typical incubation period for coronaviruses (Chen et al., 2020; Jing et al., 2020; Li et al., 2020; Linton et al., 2020). The average values of air temperature, humidity, and pressure were calculated and compared with the reproduction numbers on those days.

2.2. Reproduction number

The reproduction number indicates the average number of people that one infected person can transmit the disease to. The basic reproduction number (R_0) is used to measure the transmission potential of a disease. It is the average number of secondary infections produced by a typical case of an infection in a population where everyone is susceptible. In contrast, the effective reproductive number (R) is the average number of secondary cases per infectious case in a population composed of both susceptible and non-susceptible hosts. Therefore, not all contacts will become infected and the average number of secondary cases per infectious case will be lower than the basic reproduction number (R_0). The basic (R_0) and effective (R) reproduction numbers are calculated as follows:

$$R_0 = \beta D \quad (1)$$

$$\beta = C p \quad (2)$$

$$R = R_0 S_p \quad (3)$$

where R_0 is the basic reproduction number, β is the transmission rate, D is the duration of infectiousness, C is the rate at which contact occurs, p is the transmission probability, and S_p is the susceptible ratio of the host population.

The effective reproduction number (R) was calculated using the susceptible, exposed, infectious, and recovered (SEIR) compartmental model (van den Driessche, 2017) and software (Cori et al., 2013).

3. Kinematic air viscosity

Kinematic viscosity is defined as a measure of a fluid's internal resistance to flow under gravitational forces. The mass density (ρ) of air can be calculated from the air temperature and pressure.

$$\rho = \frac{P \cdot M_0}{R^* \cdot T_M} = \frac{0.0034837P}{T + 273.15} \quad (4)$$

The reference-level value is $P_0 = 101,325.0 \text{ N/m}^2$, which is the defined value at sea level, where P is pressure, M is mean molecular weight (sea-level value: M_0), and T_M is molecular-scale temperature.

The gas constant, $R^* = 8.31432 \times 10^3 \text{ N} \cdot \text{m}/(\text{kmol} \cdot \text{K})$, is consistent with the carbon-12 scale.

The coefficient of dynamic viscosity, $\mu \text{ (N} \cdot \text{s/m}^2\text{)}$, is defined as a coefficient of internal friction developed where gas regions move adjacent to each other at different velocities.

$$\mu = \frac{\beta \cdot T_M^{\frac{3}{2}}}{T_M + S} = 1.458 \times 10^{-6} \times \frac{(T + 273.15)^{\frac{3}{2}}}{T + 383.55} \quad (5)$$

$$\eta = \mu / \rho \quad (6)$$

S , independent of temperature; T , temperature ($^{\circ}\text{C}$); T_M , $T + 273.15 \text{ (K)}$; $\beta = 1.458 \times 10^{-6} \text{ [kg}/(\text{s} \cdot \text{m} \cdot \text{K}^{1/2})]$; μ , coefficient of dynamic viscosity; η , kinematic viscosity

3.1. Statistical analysis

All statistical analyses were conducted using SPSS version 22 software (IBM, Armonk, NY, USA), and p -values < 0.05 were considered statistically significant. In regression analysis, scatter plots were constructed, with temperature or humidity on the horizontal axis and the reproduction number on the vertical axis to obtain linear and quadratic scatter plot fit lines, respectively. The association between reproduction numbers (more than 4) and average air temperature and humidity was analyzed using receiver operating characteristic (ROC) curves to evaluate the precision of screening using the reproduction number (Lloyd, 2000).

4. Results

4.1. Subjects

A total of 1018 subjects (males = 506, females = 512; age range = less than 10–90 years) out of 1263 people were enrolled in this study. The remaining patients (245) who refused to disclose their personal information were excluded. The incidence of COVID-19 and the average reproduction number (R) over time periods are shown in Fig. 1. Three main peaks of R were identified; soon after, the transmission was dramatic.

4.2. Reproduction numbers in the five different areas of Hokkaido

Hokkaido, which is located in the northern part of Japan, has a large mountain range at its center and is surrounded by bodies of water: the Sea of Japan, the Sea of Okhotsk, and the Pacific Ocean (Fig. 2A). The weather conditions, such as air temperature and humidity, in each of Hokkaido's five areas, namely the Sea of Japan coast, Inland, the Sea of Okhotsk coast, Eastern Pacific, and Western Pacific, have completely different characteristics (Figs. 2B, C). The average values of the reproduction numbers in these areas were 1.51, 1.89, 1.75, 2.39, and 2.28, respectively.

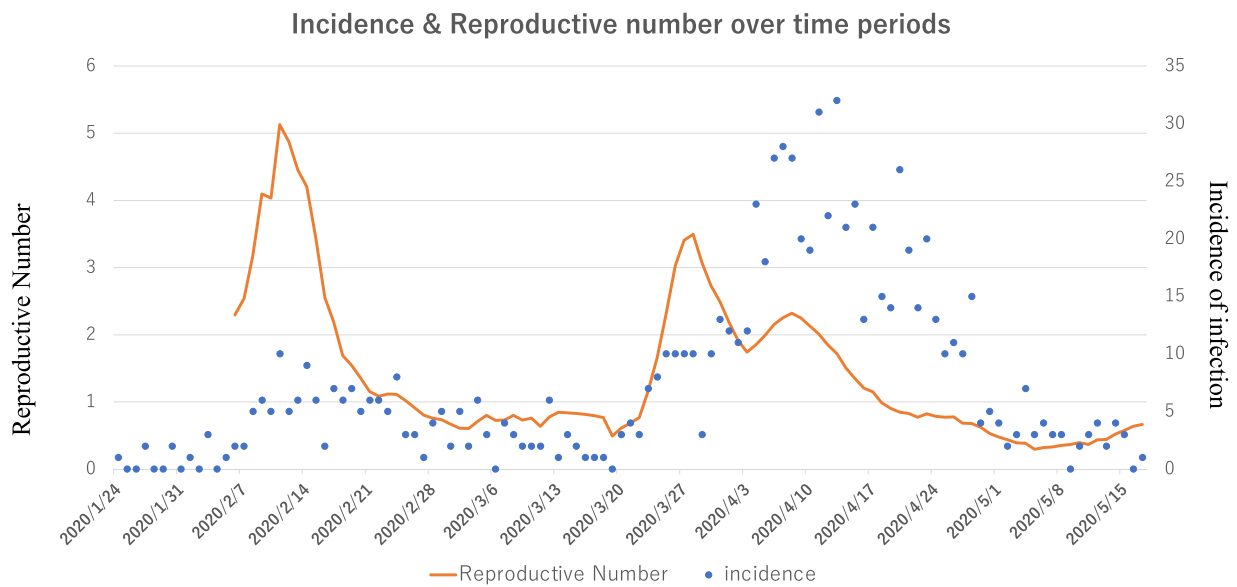


Fig. 1. The incidence of COVID-19 infection and average reproduction number (R) over time periods are depicted here. Three main peaks were identified during the study period; the peaks in the reproduction number appeared several days before the peaks in incidence. Continuously high reproduction numbers during the second and third peaks might have induced the peaks in incidence.

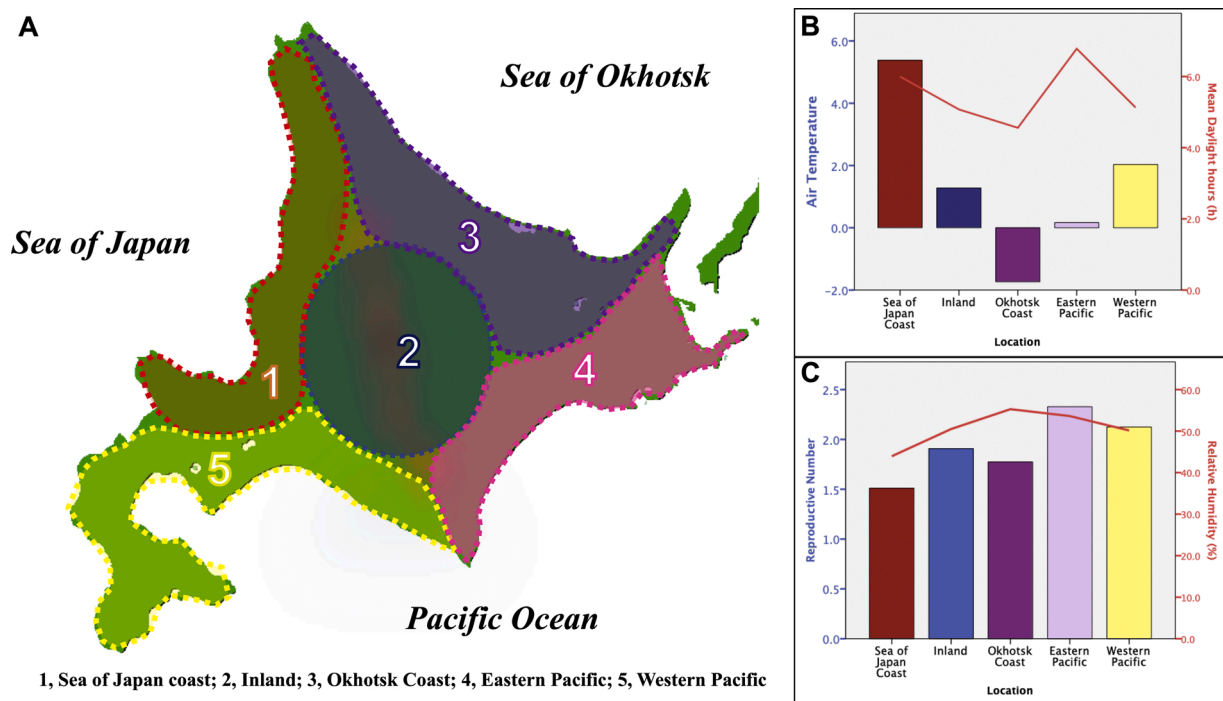


Fig. 2. A shows the five major areas in Hokkaido classified based on climate differences. The meteorological parameters, such as air temperature (bar graph in Fig. 2B), daylight hours (red line in Fig. 2B), and humidity (red line in Fig. 2C), and the average values of the reproduction number (bar graph in Fig. 2C) are totally different in each area.

4.3. Correlation between reproduction number and meteorological variables

Scatter diagrams (Figs. 3A and B) reveal the distribution of COVID-19 incidence in tandem with air temperature and humidity. Figs. 3C, D, and E depict the ROC curve analysis for the reproduction number, where the cut-off value was fixed at 4.0. Fig. 3F shows a high degree of negative correlation between air temperature and the reproduction number ($r = -0.424, p < 0.001$), while Fig. 3G shows a weak degree of positive correlation between humidity and the reproduction number ($r = 0.139, p < 0.001$).

The highest reproduction number (5.13) was observed when the temperature was cold, suggesting that COVID-19 incidence is more likely to increase at -10°C in the winter season. Overall, the effects of humidity on incidence in Hokkaido are presented in Fig. 3B. A reproduction number greater than four was observed for humidity levels of 60%–80%, suggesting that COVID-19 incidence is most likely to increase at that humidity. Air viscosity was calculated using the atmospheric temperature, humidity, and pressure. Atmospheric air viscosity presented a high degree of negative correlation with the reproduction number ($r = -0.457, p < 0.001$), as shown in Fig. 3H.

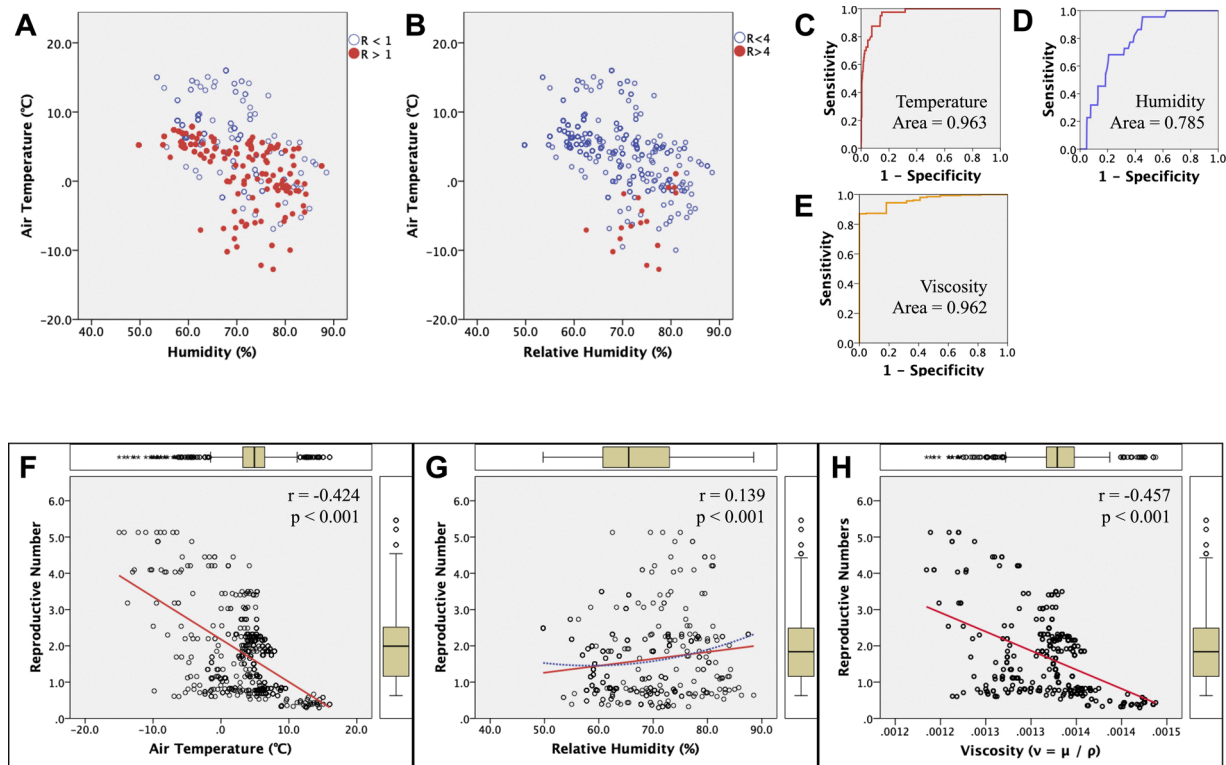


Fig. 3. Scatter diagrams (Figs. 3A, B) show the distribution of COVID-19 incidence in tandem with air temperature and humidity. The open white circles mark the incidences with reproduction numbers (R) less than 1 and 4 in Fig. 3A, and the red circles mark the incidences with R more than 1 and 4 in Fig. 3B. Receiver operating characteristic (ROC) curve analysis (Figs. 3C-E) is shown for R , with the cut-off value at 4.0. Scatter diagrams (Figs. 3F-H) reveal correlations between R and air temperature (F), humidity (G), and air viscosity (H). A strong negative correlation was detected between R and air temperature ($r = -0.424$, $p < 0.001$), while a weak association was observed between R and humidity ($r = 0.139$, $p < 0.001$). Moreover, a strong negative correlation existed between R and air viscosity ($r = -0.457$, $p < 0.001$).

5. Discussion

Since the start of the COVID-19 pandemic, every country has been struggling to curb the spread of the virus, and some positive results have been seen recently. Various research organizations worldwide have been studying the characteristics of SARS-CoV-2, but much remains unknown about the virus, including whether seasonal factors affect transmission. It is known that some viral infections are more prevalent in summer and others in winter. Some classes of viruses, such as rhinoviruses, adenoviruses, and influenza viruses, can live longer in a colder and drier environment. It is also possible that people get infected more easily as they tend to gather indoors in winter to ward off the cold weather. In contrast, there are some viral infections, such as hand-foot-and-mouth disease and herpangina, which are caused by different strains of coxsackie virus and pharyngoconjunctival fever (adenovirus) that are more common in summer. The main route of COVID-19 transmission is through the inhalation of droplets when an infected person coughs or sneezes. Aerosol transmission of SARS-CoV-2 among the close contacts of people has recently been reported. The potential of airborne viral diffusion has also been analyzed in some recent studies (Dbouk and Drikakis, 2020; Liu et al., 2020a, b; Santarpia et al., 2020; Setti et al., 2020). However, it is still unclear if airborne or aerosol infections can occur. Infection is also possible when a person's hands come in contact with their eyes, nose, or mouth after touching a contaminated surface. In such instances, the virus needs to survive on the surface under certain environmental conditions. Some studies have demonstrated that temperature and humidity are significantly correlated with viral survival and transmission rates on surfaces (Harper, 1961; Metz and Finn, 2015; Pinheiro et al., 2014; Wang et al., 2020). Additionally, recent reports have shown that sunlight could rapidly inactivate airborne SARS-Cov-2 (Schuit et al., 2020; Dabisch et al., 2020; Smither et al., 2020). Arundel

and Sterling (1986) concluded that relative humidity does not influence the incidence of a viral infection in a highly ventilated and fresh environment. During outbreaks in healthcare facilities, surface sampling for the classic SARS coronavirus (SARS-CoV) revealed the presence of the virus' nucleic acids on surfaces and inanimate objects, suggesting that surfaces could be a source of viral transmission (Booth et al., 2005; Dowell et al., 2004). Survival times of SARS-CoV-2 on certain surfaces have also been reported recently (Hirose et al., 2020; van Doremalen et al., 2020). According to the results of those studies, the survivability of SARS-CoV-2 on surfaces of different materials at 4° – 5° C, 20° – 22° C, and 30° – 40° C is more than 28 days, 3–9 days, and a few hours, respectively (van Doremalen et al., 2020). Due to their simple structure, viruses cannot multiply on their own. DNA or RNA (RNA, in the case of coronaviruses) is enclosed in the body of the virus, and the genetic information is covered in a lipid bilayer membrane envelope. Corona- or crown-like protein projections on the surface are characteristic of SARS-CoV-2. It has been reported that viruses with lipid envelopes, such as influenza viruses, respiratory syncytial virus, and herpes viruses, are more stable at lower levels of humidity, whereas non-lipid enveloped viruses, such as respiratory adenoviruses and rhinoviruses, survive longer at higher levels of humidity (Arundel et al., 1986; Cox, 1989; Cox and Fukuda, 1998; Harper, 1961; Hermann et al., 2007; Ijaz et al., 1985; Karim et al., 1985; Schaffer et al., 1976). Some studies have recently reported correlations between meteorological conditions and COVID-19 transmission in Asia (Fareed et al., 2020; Kodera et al., 2020; Poirier et al., 2020), Africa (Meo et al., 2020a; Ogaugwu et al., 2020), Latin America (Bolano-Ortiz et al., 2020) and Europe (Meo et al., 2020b). Meteorological factors, such as temperature and humidity, might affect not only human-to-human transmission, but also viral stability and host immunity. For example, a dry environment might cause desiccation of the nasal mucosa, leading to muco-epithelial damage and damage to the

mucociliary clearance system (Schaffner et al., 1976).

The question of whether it is possible to get infected via aerosol might be answered by considering atmospheric air viscosity. The kinematic viscosity of atmospheric air, which can be calculated from air temperature, humidity, and pressure, might affect COVID-19 infection. In this study, we showed a strong association between COVID-19 incidence and meteorological factors, such as the kinematic viscosity of atmospheric air. Some reports have demonstrated that the spread of contaminants is associated with meteorological factors (Bolano-Ortiz et al., 2020; Dbouk and Drikakis, 2020; Fareed et al., 2020; Meo et al., 2020a; Ogaugwu et al., 2020; Poirier et al., 2020; Sarkodie and Owusu, 2020). Airborne transmission of SARS-CoV-2 has recently been reported in hospitals in Wuhan. Lower quantities of SARS-CoV-2 RNA were retrieved from air samples collected from outside hospital buildings compared to indoors (Setti et al., 2020). Atmospheric particulates or droplets can carry SARS-CoV-2 (Carraturo et al., 2020), and the viscosity of atmospheric air affects the spread of organic particles (Reid et al., 2018). Our results show that a lower atmospheric air viscosity could induce a higher incidence of COVID-19.

Generally, when it is too cold or warm outside with high humidity, people tend to stay indoors, thereby increasing their contact frequency. With decreased temperatures in the winter season, the tendency of people to gather indoors is expected in the northern hemisphere (Scarfetta, 2020). In Hokkaido, while outside temperatures vary from -13° to 8.5°C , indoor temperatures are maintained around 20° – 23°C under recirculating air-conditioning (supplementary data). This would promote closer contact among people, which might cause a wider spread of infection.

The reproduction number is the average number of secondary infections produced by one infected individual. In general, R is calculated using the SEIR model, which was proposed as part of the Kermack-McKendrick theory (Kermack and McKendrick, 1927). R can indicate the progress of transmission as follows:

$R = 1$: One infectious person produces one new infection → Endemic stage

$R > 1$: An infectious person infects more than one person. → The epidemic will spread

$R < 1$: An infectious person infects less than one person. → The epidemic will slow down

The degree of immunity in a population could gradually increase. Even if the R_0 is more than 1, the epidemic would not continue after a large number of people acquire immunity (herd immunity) because R would be less than 1. In this study, the reproduction numbers had three peaks, which appeared several days before the incidence of COVID-19 (clusters). However, the incidence peak after the first peak of the reproduction number was low. This discrepancy may be explained by the fact that PCR testing for COVID-19 was not popular in Japan at that time. The incidence of COVID-19 infection in February could not show the real incidence, and lately, PCR testing has been gradually used to detect infected individuals.

It is necessary to reduce the rate of contact through quarantine, isolating infected cases from others, and also cut transmission probability (p) through vaccination and/or treatment with medications as well as via preventive measures such as wearing a mask. Therefore, reducing R is essential for suppressing the COVID-19 pandemic.

Since the peaks in R were seen just before the start of cluster infections in this study, it is possible to predict an epidemic or cluster beforehand. Additionally, the possibility that cluster infections are more likely to occur in winter than in other seasons needs to be considered.

6. Limitations

This study has some limitations. First, since only local data were analyzed, the results may not be universally applicable. Second, using cross-sectional data in a meteorological study did not allow us to confirm a causal relationship or control for confounding factors. Third,

there was no *in vivo* data on the relationship between SARS-CoV-2 and air viscosity. Lastly, there were no data on the indoor environments in each area.

7. Conclusion

The authors demonstrated a strong association between disease incidence or reproduction number and meteorological factors, such as air temperature and air viscosity. As exterminating the novel coronavirus that causes COVID-19 is impossible, it is necessary for people across the world to think about how to fight against and coexist with this virus. Air temperature, humidity, and viscosity could affect viral survival, viral spread via aerosol, and even human behavior indoors. Given the approaching winter season in the northern hemisphere, it is important to keep in mind that the COVID-19 pandemic is not over yet.

Authorship

Author contributions to the study and manuscript preparation are as follows: Conception and design: Akiyama; Acquisition of data: Sakashita, Arihara, Kimura, Komatsu, and Mikami; Statistical analysis: Akiyama and Mikami; Drafting of the article: Akiyama; and critical revision of the article: All authors.

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CRediT authorship contribution statement

Yukinori Akiyama: Conceptualization, Methodology, Writing - original draft, Data curation. **Kyoya Sakashita:** Data curation. **Masayasu Arihara:** Investigation. **Yusuke Kimura:** Investigation. **Katsuya Komatsu:** Validation. **Takeshi Mikami:** Writing - review & editing. **Nobuhiro Mikuni:** Supervision.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.virusres.2020.198259>.

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