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Association of COVID-19 pandemic with meteorological parameters over Singapore

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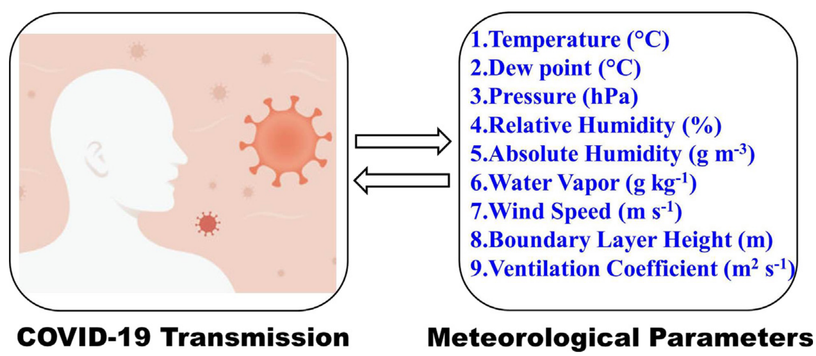
HIGHLIGHTS

- COVID-19 is an emerging infectious disease and highly contagious in nature.
- Temperature, dew point, and absolute humidity showed positive significant associations with SARS-CoV-2 transmission.
- SARS-CoV-2 displayed negative associations with wind speed and ventilation coefficient.

GRAPHICAL ABSTRACT



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ABSTRACT

Meteorological parameters are the critical factors affecting the transmission of infectious diseases such as Middle East Respiratory Syndrome (MERS), Severe Acute Respiratory Syndrome (SARS), and influenza. Consequently, infectious disease incidence rates are likely to be influenced by the weather change. This study investigates the role of Singapore's hot tropical weather in COVID-19 transmission by exploring the association between meteorological parameters and the COVID-19 pandemic cases in Singapore. This study uses the secondary data of COVID-19 daily cases from the webpage of Ministry of Health (MOH), Singapore. Spearman and Kendall rank correlation tests were used to investigate the correlation between COVID-19 and meteorological parameters. Temperature, dew point, relative humidity, absolute humidity, and water vapor showed positive significant correlation with COVID-19 pandemic. These results will help the epidemiologists to understand the behavior of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) virus against meteorological variables. This study finding would be also a useful supplement to help the local healthcare policymakers, Center for Disease Control (CDC), and the World Health Organization (WHO) in the process of strategy making to combat COVID-19 in Singapore.

1. Introduction

Coronavirus disease 2019 (COVID-19; previously known as 2019-nCoV) outbreak is associated with the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), which is a novel coronavirus with a probable bat origin (Zhou et al., 2020a; Lam et al., 2020), that originated in the area of Wuhan, Hubei province, China, in late December

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of 2019 (Huang et al., 2020; Wu et al., 2020a, 2020b). SARS-CoV-2 is a single-stranded positive-sense RNA virus (Satija and Lal, 2007) with diameter ranging from 60 to 140 nm (Hsiao et al., 2020; Zou et al., 2020). The reproduction number of SARS-CoV-2 is close to or slightly higher than Middle East Respiratory Syndrome Coronavirus (MERS-CoV) and SARS-CoV-1 (Lipsitch et al., 2003; Wallinga and Teunis, 2004; Lin et al., 2018; Zhou et al., 2020b; Lim et al., 2020). COVID-19 spreads rapidly throughout the globe due to its highly contagious nature and it was officially declared a pandemic by the World Health Organization (WHO) on March 11, 2020 (WHO, 2020a).

SARS-CoV-2 is essentially transmitted directly by human-to-human transmission via close contact (i.e., through respiratory droplets emitted from an infected person, during coughing, sneezing, laughing, and exhaling, to another healthy person) and also indirectly through the contact of contaminated surfaces (WHO, 2020b; Huang et al., 2020; Xu et al., 2020; Lai et al., 2020). Accordingly, maintaining social distancing of at least one meter, avoiding touching eyes, nose, and mouth, and frequent hand-washing and/or sanitizing are importantly advised to contract the infection (WHO, 2020c). Similar to SARS, the median incubation period for COVID-19 is also approximately five days (Lauer et al., 2020). Common symptoms of SARS-CoV-2 (based on clinical, laboratory, and radiologic characteristics) are fever, dry cough, myalgia, fatigue, dyspnea, anorexia, sore throat, nasal congestion, and headache (Wang et al., 2020; Guo et al., 2020). Serious complications associated with SARS-CoV-2 infection include multiple organ failure, pulmonary oedema, septic shock, acute respiratory stress syndrome, and severe pneumonia (Sohrabi et al., 2020; Chen et al., 2020). The most serious symptoms such as digestive, cardiovascular, endrocrine, and respiratory diseases, which required intensive therapy, are generally found in older individuals with the history of previous comorbidities (Sohrabi et al., 2020; Wang et al., 2020a; Fattorini and Regoli, 2020). There is no specific medication and pharmacological treatment for COVID-19 as yet (Cortegiani et al., 2020). By May 31, 2020, there was 6,259,249 and 373,697 numbers of confirmed cases and deaths, respectively, reported over the globe due to COVID-19 (https://www.worldometers.info/coronavirus/).

Recently, the airborne transmission was reported as a probable transport pathway to spread SARS-CoV-2 (Bourouiba, 2020; van Doremalen et al., 2020; Morawska and Cao, 2020; Buonanno et al., 2020; Hadei et al., 2020; Stadnytskyi et al., 2020; Paules et al., 2020; Setti et al., 2020; Yao et al., 2020a). Airborne transmissions of other infectious viruses such as H5N1, influenza, Norwalk-like virus, MERS-CoV and SARS-CoV-1 are also well-documented (Marks et al., 2003; Yu et al., 2004; Roy and Milton, 2004; Herfst et al., 2012; Leitmeyer and Adlhoch, 2016; Yan et al., 2018; Xiao et al., 2018). Virus-laden larger respiratory droplets can travel only short distance and get deposited close to the emission point, while smaller can travel meters or tens of meters long distances from the emission point (e.g. Morawska et al., 2009; Fernstrom and Goldblatt, 2013; Lu et al., 2020; Morawska and Cao, 2020). Liu et al. (2020a) reported the possible propagation of SARS-CoV-2 via aerosols based on its aerodynamic nature. Lednicky et al. (2020) collected SARS-CoV-2 virus from the aerosol sample and analyzed the viral genomic sequence. Coronavirus survival and transmission by droplets are generally facilitated in dry and cold weather conditions (Casanova et al., 2010). Coronaviruses transmission can be impacted by several factors, including the weather and climate (Hemmes et al., 1962; Pica and Bouvier, 2012). Meteorological parameters are generally believed to be effective drivers in the transmission of viruses causing infectious diseases (e.g. Yuan et al., 2006; Chan et al., 2011; Pica and Bouvier, 2012; van Doremalen et al., 2013; Kutter et al., 2018; Dalziel et al., 2018). Both laboratory and epidemiological studies have shown that particularly the ambient temperature is a crucial factor in the transmission and survival of coronaviruses like MERS-CoV and SARS-CoV-1 (e.g. Tan et al., 2005; Bi et al., 2007; Casanova et al., 2010; Chan et al., 2011; van Doremalen et al., 2013). Qu and Wickramasinghe (2017) reported that high solar radiation can prevent the transmission by inactivating the MERS-CoV and SARS-CoV-1 like coronaviruses. Transmission of Influenza and pneumonia is greatly affected by meteorological parameters (Steel et al., 2011; Barreca, 2012; Barreca and Shimshack, 2012; Davis et al., 2016a, 2016b).

However, this is still debatable whether the spread of COVID-19 is being influenced by the meteorology as are other seasonal viruses (Neher et al., 2020) or not. Several recent studies investigated the effects of meteorological/weather conditions on COVID-19 transmission over different worldwide locations such as China (Shi et al., 2020; Liu et al., 2020b; Xie and Zhu, 2020; Ma et al., 2020; Qi et al., 2020), Iran (Ahmadi et al., 2020), Spain (Briz-Redón and Serrano-Aroca, 2020), the USA (Bashir et al., 2020; Gupta et al., 2020), Mexico (Méndez-Arriaga, 2020), Turkey (Sahin, 2020), Brazil (Auler et al., 2020; Prata et al., 2020), Indonesia (Tosepu et al., 2020), Norway (Menebo, 2020) and also over the globe (Sobral et al., 2020; Wu et al., 2020a). Conclusions about the effect of meteorological conditions on COVID-19 transmission are still controversial. Evidences published on COVID-19 so far has not certainly resolved that weather condition is a key modulator of the SARS-CoV-2 transmission (e.g. Yao et al., 2020b; Gunthe et al., 2020; Gupta et al., 2020; Liu et al., 2020b; Xie and Zhu, 2020; Tobías and Molina, 2020). Nevertheless, there is still an insufficiency of evidence. Moreover, the WHO also states that vigorous studies are required to improve forecasting models and to adopt public health measures. Therefore, investigations of COVID-19's weather dependency in different regions or countries or cities are important to enhance the present understanding about its spread.

Southeast Asia (SEA; here defined as Singapore, Indonesia, Philippines, Malaysia, Thailand, Vietnam, Myanmar, Brunei, Cambodia, and Laos), a well-known region for its high pollution loadings and complex meteorology (Lin et al., 2013; Salinas et al., 2013; Tsay et al., 2016; Kusumaningtyas et al., 2018; Khamkaew et al., 2016; Pani et al., 2016a, 2016b, 2018, 2019a, 2019b, 2020; Hien et al., 2019; Tham et al., 2019; Dahari et al., 2020), has been hit hard by the COVID-19 pandemic with a surge of new cases recently (Fig. 1). The total number of reported cases and deaths, associated with COVID-19 pandemic in SEA as of May 31, 2020, were 91,180 and 2773, respectively (https://www.worldometers.info/coronavirus/). Among the SEA countries, the highest number of total cumulative cases was reported for Singapore (Fig. 2). Singapore, an urban agglomeration in maritime SEA, declared its first case of COVID-19 (imported case in relation to a 66-year old male Chinese national from Wuhan) on January 23, 2020 (Lim et al., 2020). This country had shown prompt and aggressive response to contain COVID-19 via massive screening of individuals' temperatures, widespread testing and monitoring, enacted extensive surveillance, detailed contract tracing, mandatory quarantines and isolations for all overseas returning travelers, confirmed cases, and those in contact with them. But in spite of its early success, Singapore has had the highest number of total confirmed cases in SEA since April 20, 2020 following an outburst of infections linked to dormitories of foreign workers (Center for Strategic and International Studies, 2020). As COVID-19 rumbles on, scientists and researchers are investigating its features from every feasible angle including recognizing the factors that can reduce the speed of its spread. Although there are many controlling factors, this study mainly investigates the association of COVID-19 with various meteorological parameters in Singapore.

2. Data and methodology

2.1. A brief about Singapore

Singapore, an industrialized and urbanized city-state and island country, lies off the southern tip of Malay Peninsula in maritime SEA. It is separated from Indonesia's Riau Islands by the Singapore Strait to the south and by the narrow Johore Strait in the north from Peninsular Malaysia. It covers approximately an area of 722.5 km^2 as at end of June 2018 (Department of Statistics, 2019), with a recent population density of about 7953 persons per km (http://data.worldbank.org/indicator/EN.

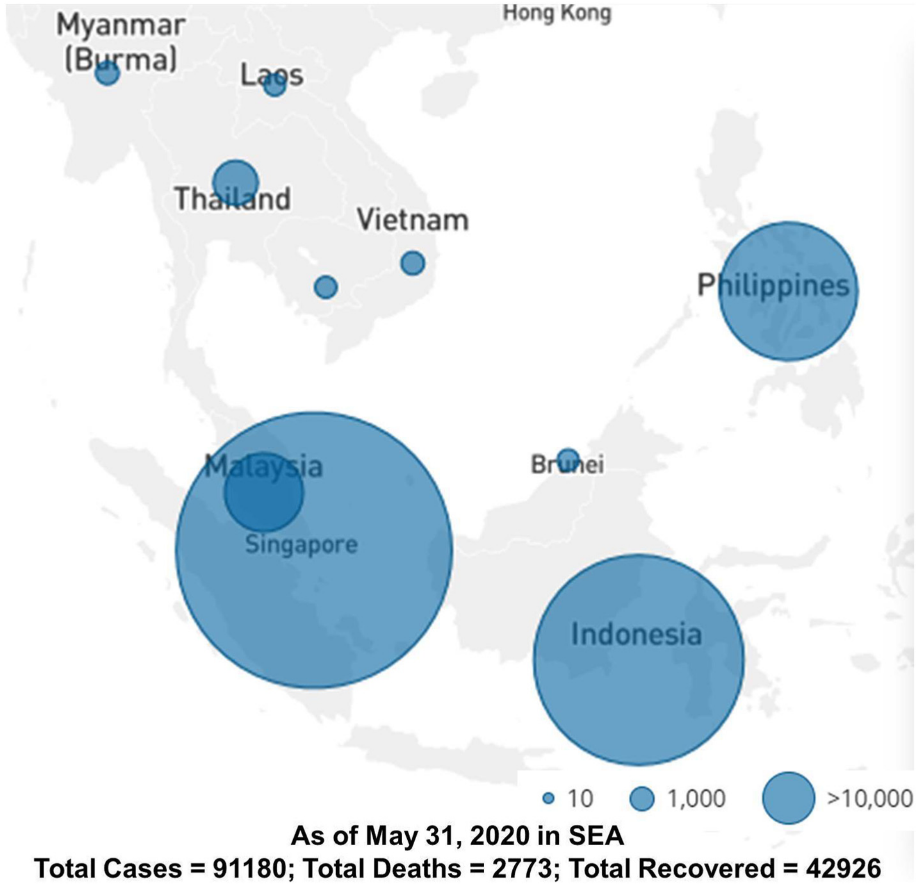

Fig. 1. Geographical locations and cumulative confirmed COVID-19 cases of Southeast Asian countries as of May 31, 2020 (the map is adopted from Center for Strategic and International Studies, 2020).

POP.DNST). Owing to its geographical location (1.15–1.48°N and 103.6–104.42°E) and maritime exposure, Singapore is subject to a hot and humid climate with abundant rainfall. Singapore's climate is mainly characterized by two different monsoon seasons namely southwest monsoon (June to September) and northeast monsoon (December to early March) separated by inter-monsoon periods (i.e., October–November and late March–May). Afternoon thunderstorms are common mostly during the inter-monsoon periods (Department of Statistics, 2019). The foremost climatic concern in such a heavily populated city is the heat island effect of the highly urbanized areas (Priyadarsini et al., 2008) and thermal comfort for the inhabitants (Dear et al., 1991).

2.2. Data and estimations

Secondary data of COVID-19 pandemic for Singapore were gathered from the official website of the Ministry of Health (MOH), Singapore (https://www.moh.gov.sg/). Daily cases of new infections, recovery

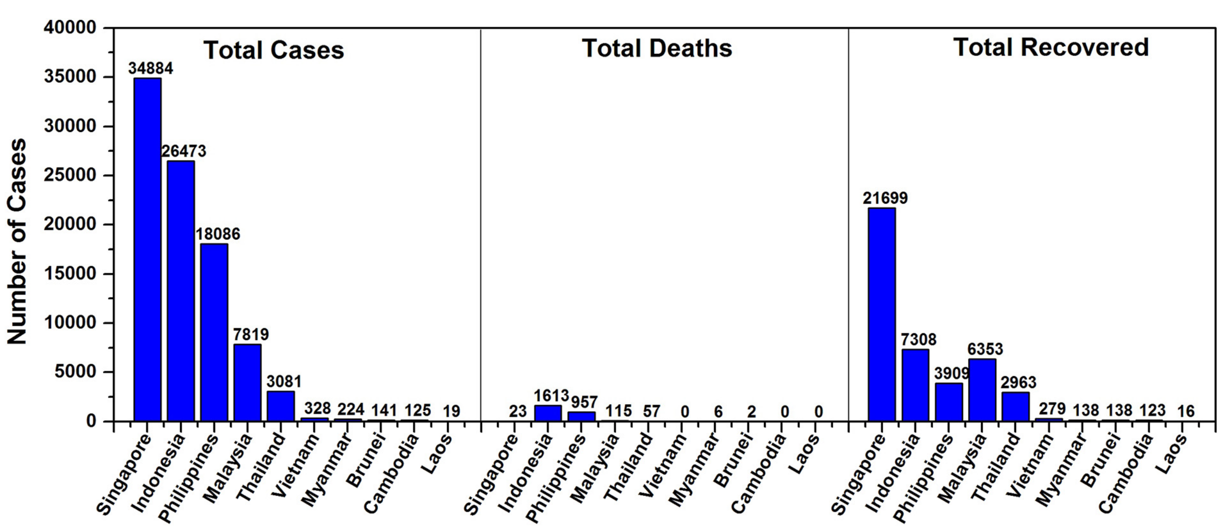

Fig. 2. Information about COVID-19 (total confirmed cumulative cases, deaths, and recovered) in Southeast Asia as of May 31, 2020.

rate i.e. number of patients discharged from the hospitals, and deaths were obtained for the period from January 23 to May 31, 2020, and included in this study.

Daily records of basic meteorological parameters, including maximum temperature (T_{max}), average temperature (T_{avg}), minimum temperature (T_{min}), maximum relative humidity (RH_{max}), average relative humidity (RH_{avg}), minimum relative humidity (RH_{min}), maximum surface pressure (P_{max}), average surface pressure (P_{avg}), minimum surface pressure (P_{min}), maximum dew point (DP_{max}), average dew point (DP_{avg}), minimum dew point (DP_{min}), maximum wind speed (WS_{max}), average wind speed (WS_{avg}), and minimum wind speed (WS_{min}), were obtained from the online database archives of the Weather Underground (http://www.wunderground.com/). The sources for this website database archives are typical weather stations, owned by government agencies, at international airports of the respective countries or cities. Likely, this website includes the weather conditions of Singapore from the Singapore Changi Airport Station (ICAO code: WSSS; https://www.wunderground.com/about/data). Weather Underground is a popular and trustworthy online platform and the data from this source has been used for various atmospheric research applications worldwide (e.g. Pani, 2013; Verma et al., 2013, 2014; Pani and Verma, 2014; Mohan et al., 2014; Vargo et al., 2015; Kumar et al., 2017; Pani et al., 2017; Golroudbary et al., 2018; Marshall et al., 2018; de Vos et al., 2019; Sahin, 2020).

Absolute humidity (AH; in g m^{-3}), the weight of water vapor per unit volume of air, was estimated using the Clausius-Clapeyron equation and can be described as follows (e.g. Qi et al., 2020a; Gupta et al., 2020),

$$AH = 2.1674 \times RH \times \frac{6.112 \times \ exp\left(\frac{17.67 \times T}{243.5 + T}\right)}{(273.15 + T)} \quad (1)$$

Likely, water vapor (WV; in g kg^{-1}) was also estimated as follows (e.g. Ou-Yang et al., 2014),

$$WV = 6.22 \times RH \times \frac{6.112 \times \ exp\left(\frac{17.67 \times T}{243.5 + T}\right)}{P} \quad (2)$$

Atmospheric boundary layer height (ABLH), as the level of the maximum vertical gradient of potential temperature (Stull, 1988; Seidel et al., 2010), over Singapore was estimated using the radiosonde data (at 12 UTC) from the University of Wyoming database archive (Station ID: WSSS; http://weather.uwyo.edu/upperair/sounding.html).

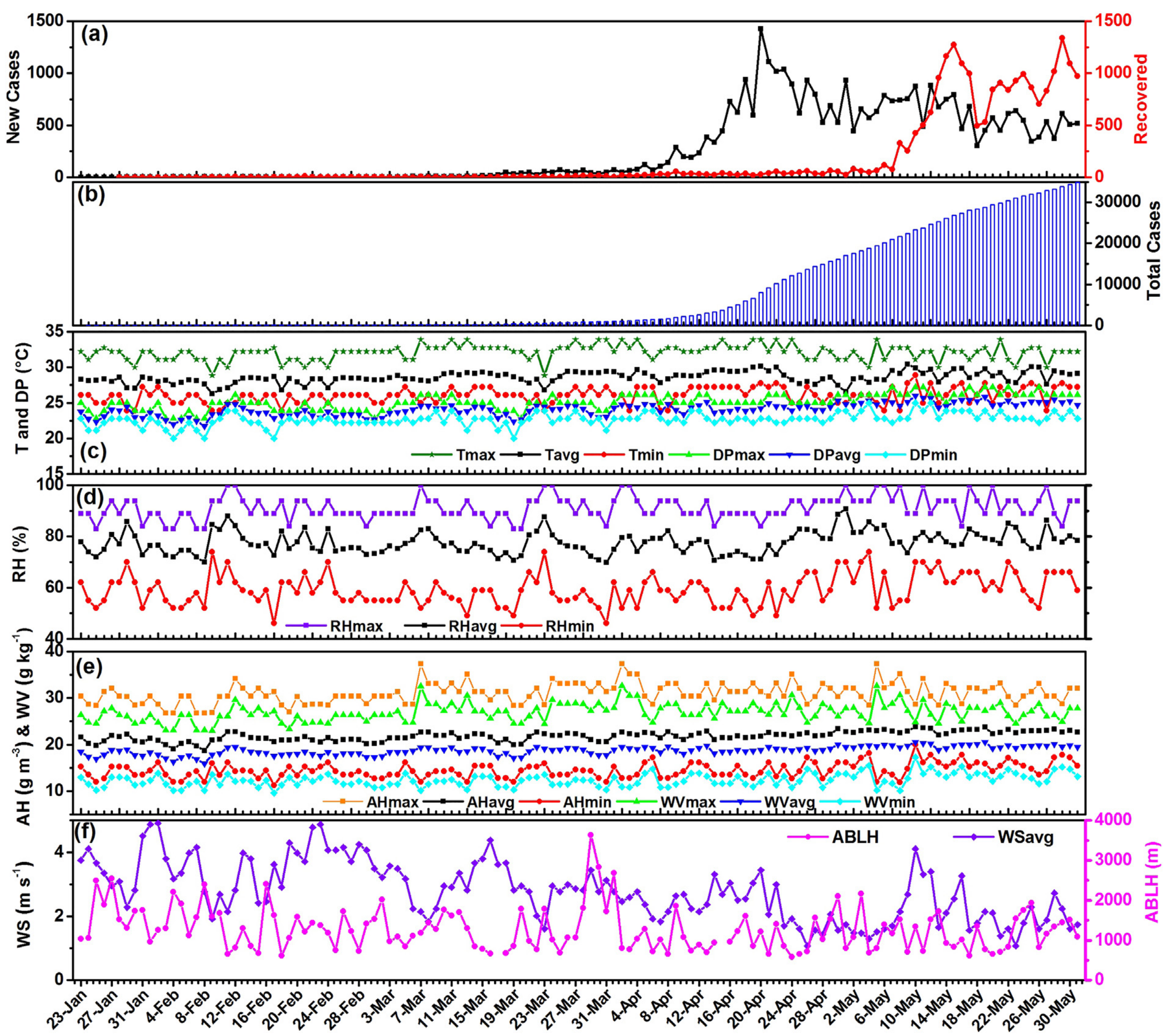

Fig. 3. (a, b) Cases of COVID-19 in Singapore. Day-to-day variations in (c) T and DP (°C), (d) RH (%), (e) AH (g m^{-3}) and WV (g kg^{-1}), and (f) WS (m s^{-1}) and ABLH (m) over Singapore from January 23 to May 31, 2020.

2.3. Statistical approaches

Spearman and Kendall rank correlation tests were used to examine the associations between COVID-19 and meteorological parameters in this current study. Spearman rank correlation, a non-parametric test, measures the strength of association between two variables. Spearman rank correlation coefficient i.e. Spearman's Rho (r_s) can be estimated as following,

$$r_s = 1-6 \times \frac{\sum d_i^2}{n(n^2-1)} \tag{3}$$

where d_i represents the difference between the ranks of two parameters and n represents the number of alternatives. The value of $r_s = +1$ and -1 means a perfect positive and negative correlation, respectively.

Kendall rank correlation, also another non-parametric test, used to measure the ordinal association between two measured variables. Kendall rank correlation coefficient, also called Kendall's tau (τ), is used to evaluate the similarity of the orderings between two datasets and can be used estimated as following

$$\tau = \frac{[(concor)-(discor)]}{0.5 \times n \times (n-1)} \tag{4}$$

where *concor* and *discor* represents the number of concordant and discordant pairs, respectively. The n represents the number of pairs. The value of τ ranges from -1 to $+1$ and has a similar interpretation as Spearman's correlation. In this current study, we used XLSTAT software (https://www.xlstat.com/en/) to perform the above-mentioned statistical calculations.

3. Results and discussion

3.1. Daily variations of COVID-19 cases and meteorological parameters

As of May 31, 2020, the reported numbers of total cases, deaths, and recovered with respect to COVID-19 pandemic over Singapore were 34,884, 23, and 21,699, respectively (Fig. 2). Daily counts of COVID-19 new infection and recovered cases, from January 23 to May 31, 2020, in Singapore are shown in Fig. 3a. The first case of local human-to-human transmission in Singapore was officially reported on February 4, 2020 (https://www.moh.gov.sg/news-highlights). Despite of the enforcement of lockdown in the country to minimize further spread of COVID-19 (https://www.moh.gov.sg/news-highlights/details/circuit-breaker-to-minimise-further-spread-of-covid-19), data showed a sharp increase in daily new cases from April 7, 2020 onwards and reached the maximum peak on April 23 (Fig. 3a). However, the recovery rate was found higher during May 2020 as compared to previous months (Fig. 3a).

Daily variations in different meteorological parameters in Singapore are shown in Fig. 3 and their descriptive statistical analyses are presented in Table 1. T was recorded as high as 34 °C and as low as 24 °C. DP is the temperature to which air must be cooled to become saturated without changing the pressure and this is greatly associated with the human comfort. Over Singapore, DP_{avg} ranged between 20 °C and 27 °C (Fig. 3c) and indicated the uncomfortable levels and possible heat stress issues for the human in outdoor. RH mainly depends on the temperature and pressure of the environment. It is the ratio of actual WV pressure to the saturation WV pressure at the prevailing temperature. RH was recorded as low as 46% and as high as 100% over Singapore during the study period (Fig. 3d). Similar to RH, large day-to-day variations were also seen in cases of AH and WV (Fig. 3e) over Singapore. WS_{avg} ranged between 1.1 and 4.9 m s^{-1} (Fig. 3f) with the mean value of 2.8 ± 0.9 m s^{-1}.

ABLH, height of the lowest part of the troposphere that directly feels the effect of the earth's surface, plays an important role in the weather modulation over a region. ABLH depends on several factors such as geographical location, topography, vegetation cover, surface and vertical wind distributions, and urban roughness (Stull, 1988; Garratt, 1992). The estimated median value of ABLH over Singapore in this study (at 08:00 pm local time) was found to be 1175 m. Ventilation coefficient (VC in m^2 s^{-1}; the product of WS_{avg} and ABLH) was estimated and analyzed in order to understand the air pollution potential over the urban agglomeration of Singapore. VC plays an important role in the dispersion of air pollutants (Saha et al., 2019). Lower VC value indicates less dispersion of pollutants in the atmosphere, and vice-versa. The median VC value was found to be 3076 m^2 s^{-1} over Singapore during the study period (Table 1). High value of kurtosis for WS_{min}, ABLH, and VC may be explained by long periods of low values, followed by short periods of comparatively high values.

Table 2 summarizes the monthly variations of different meteorological parameters in Singapore. As compared to other basic meteorology, relatively high variations in RH_{avg} and WS_{avg} were observed. The highest RH_{avg} was found in May (80 ± 4%). WS_{avg} was the lowest in May (2.1 ± 0.7 m s^{-1}) and the highest in February (3.6 ± 0.8 m s^{-1}). ABLH also greatly varied and showed a decreasing trend from January to May. Consequently, the lowest VC was estimated for May (2380 ± 1176 m^2 s^{-1}), indicating the highest air pollution potential in that month. This may be a reason for high infections in May (Table 2), since SARS-CoV-2 can remain viable in aerosols for hours (van Doremalen et al., 2020).

3.2. Correlation between COVID-19 and meteorological parameters

As the first case of local SARS-CoV-2 transmission was reported on February 4, 2020 in Singapore, hence the daily data (both meteorological parameters and COVID-19 cases) from February 4 to May 31, 2020 were used for the correlation tests. Table 3 summarizes the results of Spearman and Kendall rank correlation tests. Temperature (T), a fundamental factor in human living environment, can play an important role in public-health concerning epidemic development, prevention, and control (McMichael et al., 2008; Tobías and Molina, 2020). T_{avg}, T_{min}, DP_{max}, DP_{avg}, and DP_{min} showed significant positive correlations with new as well as total COVID-19 cases over Singapore (Table 3). However, T_{max}, T_{avg}, and T_{min} showed relatively strong associations with COVID-19 cases over Singapore during early phase of the transmission (February 4 – April 30, 2020; Supplemental Table S1). But, DP_{max}, DP_{avg}, and DP_{min} showed higher associations in case of up-to-date dataset (February 4 to May 31, 2020; Table 3) as compared to early phase of the transmission (February 4 – April 30, 2020; Supplemental Table S1). A positive linear relationship was revealed in between the mean temperature and the number of COVID-19 cases, between January 23 and February 29, 2020, with a threshold of 3 °C in 122 cities (including Wuhan) from China (Xie and Zhu, 2020). However, Xie and Zhu (2020) also concluded that there is no evidence in support of the declination of COVID-19 in warmer weather conditions. On the contrary, Liu et al. (2020b) highlighted that lower temperature and humidity were likely to favor the COVID-19 transmission, between January 20 and March 2, 2020, in 130 Chinese cities (except Wuhan). Different from the conclusions of both above studies, Yao et al. (2020b) reported that there is no association in between COVID-19 transmission and temperature or UV radiation in Chinese cities. Méndez-Arriaga (2020), based on the data from 31 states and capital of Mexico, found the negative association of temperature with COVID-19 cases and concluded that the tropical climate (mean T around 25.95 °C and mean rainfall around 8.74 mm) can delay the local transmission onset. Tobías and Molina (2020) described an inverse relationship between ambient temperatures and COVID-19 transmission in the Barcelona health region. Likely, Shi et al. (2020) reported an inverse but significant association between temperature and COVID-19 daily incidence and also claimed that the temperature as an important environmental driver of the COVID-19 outbreak in China. Inverse relationship of ambient temperature with SARS-CoV-1

Table 1
Descriptive statistical analyses of meteorological parameters (January 23 – May 31, 2020; N = 130) in Singapore.

Parameters	Min	Max	Mean	SD	Median	Mode	Kurtosis	Asymmetry
T_{max} (°C)	29	34	32	1	32	32	0.5	−0.6
T_{avg} (°C)	26	30	29	1	29	28	0.0	−0.3
T_{min} (°C)	24	29	26	1	26	26	−0.5	−0.3
DP_{max} (°C)	23	27	25	1	25	25	−0.3	−0.2
DP_{avg} (°C)	22	26	24	1	24	23	−0.5	−0.3
DP_{min} (°C)	20	25	23	1	23	23	1.3	−0.3
P_{max} (hPa)	1006	1013	1012	1	1013	1013	1.2	−1.6
P_{avg} (hPa)	1006	1013	1010	2	1009	1009	1.3	0.5
P_{min} (hPa)	1002	1009	1007	2	1006	1006	−0.7	0.0
RH_{max} (%)	83	100	91	5	89	89	−0.3	0.2
RH_{avg} (%)	70	91	78	4	77	79	−0.1	0.5
RH_{min} (%)	46	74	59	6	59	55	−0.4	0.3
AH_{max} (g m^{-3})	27	37	31	2	31	30	0.4	0.4
AH_{avg} (g m^{-3})	19	24	22	1	22	22	−0.1	−0.5
AH_{min} (g m^{-3})	11	20	14	2	14	13	0.1	0.5
WV_{max} (g kg^{-1})	23	33	27	2	27	26	0.4	0.4
WV_{avg} (g kg^{-1})	16	21	19	1	19	19	−0.1	−0.4
WV_{min} (g kg^{-1})	10	17	12	1	12	11	0.2	0.5
WS_{max} (m s^{-1})	2.2	9.4	5.8	1.3	5.8	5.8	0.2	−0.4
WS_{avg} (m s^{-1})	1.1	4.9	2.8	0.9	2.8	2.8	−0.7	0.3
WS_{min} (m s^{-1})	0.4	2.7	0.9	0.6	0.9	0.4	1.8	1.5
ABLH (m)	587	3630	1273	539	1175	1786	2.4	1.3
VC (m^2 s^{-1})	768	12,497	3593	2018	3076	–	2.0	1.2

AH_{max}: maximum AH; AH_{avg}: average AH; AH_{min}: minimum AH; WV_{max}: maximum WV; WV_{avg}: average WV; WV_{min}: minimum WV.

transmission was well documented in literature (e.g. Bi et al., 2007). Holtmann et al. (2020) revealed that low ambient temperatures were associated with more accelerated advancement of COVID-19 in the early phase of the endemic. Significant association of COVID-19 pandemic with temperature average ($r_s = 0.39$; $p < 0.01$) is reported in Jakarta, Indonesia (Tosepu et al., 2020).

P_{max}, P_{avg}, and P_{min} showed an inverse relationship with COVID-19 cases over Singapore (Table 3). RH showed weak but positive significant correlation with COVID-19 cases over Singapore (Table 3). It is worth to note here that insignificant statistical results were found in case of RH during early phase of the transmission (February 4 – April 30, 2020; Supplemental Table S1) in Singapore. This indicates that the highest RH (80 ± 4%) in May favored the SARS-CoV-2 spread. Local air humidity negatively correlates with COVID-19 mortality in German federal states (Biktasheva, 2020). Bashir et al. (2020) also reported the positive correlation of COVID-19 cases with temperature and negative association with RH in New York, USA. Ma et al. (2020) reported a negative correlation of COVID-19 daily death counts with the RH ($r_s = -0.32$), but a positive association with the diurnal temperature range ($r_s = 0.44$) in Wuhan, China. Generally, AH exhibits a stronger impact than RH on virus transmissions (e.g. Gupta et al., 2020; Ma et al., 2020). Significant and positive associations of AH and WV with COVID-19 cases were found over Singapore (Table 3). Significant correlations of humidity with the survival and transmission of influenza (Metz and Finn, 2015) and SARS-CoV-1 (Chan et al., 2011) viruses were well demonstrated. van Doremalen et al. (2013) reported that either warm or humid conditions were favorable for MERS-CoV transmission. Wind is an important factor in infectious diseases transmission and it can possibly modulate the dynamics of various pathogens and vectors (Ellwanger and Chies, 2018). WS showed significant anti-correlation with COVID-19 cases over Singapore (Table 3). Similar to this study, negative correlation between COVID-19 and WS was also reported over Iran (Ahmadi et al., 2020). However, WS was positively associated with COVID-19 cases over Oslo, Norway (Menebo, 2020), New York, USA (Bashir et al., 2020) and Turkey (Sahin, 2020). ABLH and VC also showed the negative association with the COVID-19 cases over Singapore (Table 3). Overall, high values of T, AH, and WV along with low WS during May (Table 2) intensified the SARS-CoV-2 spread.

This study presents a new insight on the relationship of meteorological parameters with COVID-19 pandemic in Singapore and may assist local healthcare policymakers. Results from this study may help to establish a meteorology-based alert or warning system or forecasting model to facilitate timely response to upsurge of SARS-CoV-2 activity (e.g. Chong et al., 2020; Pirouz et al., 2020; Chakraborty and Ghosh, 2020; Petropoulos and Makridakis, 2020; Sardar et al., 2020). For instance, as DP showed strong positive association with COVID-19 cases in Singapore, hence the local public health authorities may issue high alert to safeguard the vulnerable groups within the population if any atmospheric forecasting model is predicting high DP values for the upcoming months. This kind of initial assessment would probably give

Table 2
Monthly variations in COVID-19 and meteorological parameters (mean ± SD) in Singapore.

	January (N = 9)	February (N = 29)	March (N = 31)	April (N = 30)	May (N = 31)
Total cases	16	86	824	15,423	18,715
T_{avg} (°C)	28 ± 1	28 ± 1	29 ± 1	29 ± 1	29 ± 1
DP_{avg} (°C)	23 ± 1	23 ± 1	24 ± 1	24 ± 0	25 ± 0
P_{avg} (hPa)	1010 ± 1	1011 ± 2	1010 ± 1	1009 ± 1	1008 ± 1
RH_{avg} (%)	77 ± 4	77 ± 5	76 ± 4	77 ± 4	80 ± 4
AH_{avg} (g m^{-3})	21 ± 1	21 ± 1	22 ± 1	22 ± 1	22 ± 0
WV_{avg} (g kg^{-1})	18 ± 1	18 ± 1	19 ± 1	19 ± 0	20 ± 0
WS_{avg} (m s^{-1})	3.4 ± 0.7	3.6 ± 0.8	3.0 ± 0.6	2.3 ± 0.6	2.1 ± 0.7
ABLH (m)	1704 ± 550	1334 ± 496	1361 ± 654	1109 ± 492	1161 ± 417
VC (m^2 s^{-1})	5741 ± 2076	4802 ± 1730	3996 ± 2179	2597 ± 1420	2380 ± 1176

Table 3
Summary of nonlinear correlation results in between COVID-19 and meteorological parameters (February 4 – May 31, 2020; N = 118) in Singapore.

Parameters	Spearman rank correlation				Kendall rank correlation			
	New cases		Total cases		New cases		Total cases	
	r_s	p[@]	r_s	p[@]	τ	p[@]	τ	p[@]
T_{max}[**]	0.14	0.12	0.12	0.20	0.11	0.12	0.09	0.18
T_{avg}[*]	0.40	<0.01	0.43	<0.01	0.33	<0.01	0.34	<0.01
T_{min}[*]	0.32	<0.01	0.35	<0.01	0.25	<0.01	0.28	<0.01
DP_{max}[*]	0.62	0	0.71	<0.01	0.48	0	0.57	0
DP_{avg}[*]	0.60	0	0.70	<0.01	0.46	0	0.57	0
DP_{min}[*]	0.41	0	0.48	<0.01	0.31	<0.01	0.37	<0.01
P_{max}[*]	−0.42	<0.01	−0.42	<0.01	−0.35	<0.01	−0.34	<0.01
P_{avg}[*]	−0.48	<0.01	−0.55	<0.01	−0.39	<0.01	−0.45	<0.01
P_{min}[*]	−0.49	<0.01	−0.48	<0.01	−0.40	<0.01	−0.41	<0.01
RH_{max}	0.19[#]	<0.05	0.23[*]	<0.01	0.14[#]	<0.05	0.18[*]	<0.01
RH_{avg}	0.21[#]	<0.05	0.27[*]	<0.01	0.15[#]	<0.05	0.18[*]	<0.01
RH_{min}	0.20[#]	<0.05	0.28[*]	<0.01	0.15[#]	<0.05	0.19[*]	<0.01
AH_{max}[*]	0.27	<0.01	0.27	<0.01	0.19	<0.01	0.19	<0.01
AH_{avg}[*]	0.59	<0.01	0.69	<0.01	0.45	0	0.55	0
AH_{min}	0.37	<0.01	0.46	<0.01	0.27	<0.01	0.34	<0.01
WV_{max}[*]	0.27	<0.01	0.27	<0.01	0.18	<0.01	0.19	<0.01
WV_{avg}[*]	0.67	<0.01	0.76	<0.01	0.51	0	0.62	0
WV_{min}[*]	0.33	<0.01	0.44	<0.01	0.25	<0.01	0.32	<0.01
WS_{max}[*]	−0.48	<0.01	−0.43	<0.01	−0.36	<0.01	−0.34	<0.01
WS_{avg}[*]	−0.61	<0.01	−0.58	<0.01	−0.45	<0.01	−0.47	<0.01
WS_{min}[*]	−0.55	<0.01	−0.59	<0.01	−0.43	<0.01	−0.46	<0.01
ABLH[**]	−0.17	0.07	−0.15	0.10	−0.11	0.08	−0.10	0.12
VC[*]	−0.48	<0.01	−0.48	<0.01	−0.33	<0.01	−0.32	<0.01

** Statistics are insignificant.
* Statistics are significant at 99% significance level.
\# Statistics are significant at 95% significance level.
@ Significance level of the two-tailed test.

rise to hypotheses for further research in epidemiology and pandemic dynamics of COVID-19 in SEA region. This study also has some limitations. Firstly, meteorological parameters were taken from one single site which may affect the statistical analyses. Secondly, as the COVID-19 is contagious in nature and primarily affected by population genetics, health infrastructure, peoples' obedience to social-distancing and social-isolation, and persons' immunity and tolerance, so more variables are actually needed to conduct a comprehensive study. Thirdly, the data about personal hygiene such as hand washing and the use of sanitizer needs to be investigated more explicitly. Fourthly, subgroup analysis including the gender and age group needs to be done to investigate the sensitive population. Lastly, virus transmission is influenced by population density (Brown et al., 2008), host behavior, defense mechanisms, and virus infectivity (Cory, 2015), and environmental determinants (Menebo, 2020).

4. Conclusions

This study mainly aims to contribute the community research by investigating the association between COVID-19 and meteorological parameters over Singapore by using statistical approaches. Our results revealed that T and DP have a positive and significant association with the number of daily as well as cumulative COVID-19 cases. SARS-CoV-2 transmission was found to be favored by high RH condition over Singapore. However, the associations of AH and WV with COVID-19 were relatively strong than that of RH. COVID-19 showed anti-correlation with WS, ABLH, and VC. This study provides needful information for the general public and local healthcare policymakers to understand the weather dependency of COVID-19 over Singapore. Further assessments of this kind are required by including large observational dataset of meteorological parameters and air-pollutants from various observation stations across the island to build a complete picture. This study is limited to the presently available facts during this global pandemic and does not claim any potential seasonal pattern for COVID-19 transmission. Active measures should be taken to control the COVID-19 transmission and further spread.

CRediT authorship contribution statement

Shantanu Kumar Pani: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing.**Neng-Huei Lin:** Visualization, Supervision. **Saginela RavindraBabu:** Data curation.

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Declaration of competing interest

The authors declare that there is no conflict of interest regarding financial funding and the publication of this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140112.

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