



Examining the roles of meteorological variables in COVID-19 spread in Malaysia

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Abstract There are limited studies that established significant relationships between meteorological variables and COVID-19 spread in Malaysia. Although knowledge from studies conducted in other countries can be utilised as a basis for the policy formulation in general, country-specific studies are necessary as meteorological parameters and COVID-19 spread vary from country to country. This study investigated the potential roles of five meteorological parameters (average relative humidity, maximum temperature, average temperature, minimum temperature, and average wind speed) on COVID-19 spread in each of the 13 states and the entire Malaysia. The state-wise daily COVID-19-confirmed cases and daily meteorological parameters from 1 August 2020 to 31 March 2021 were acquired from Ministry of Health Malaysia and Malaysia Meteorological Department, respectively. The correlations between state-wise daily COVID-19-confirmed cases and daily meteorological

parameters were ascertained via Pearson's and Spearman's correlation tests at 5% significance level. Overall, significant correlations exist between all meteorological parameters considered in this study and daily COVID-19-confirmed cases throughout Malaysia. Average wind speed was positively correlated with COVID-19-confirmed cases, whereas average relative humidity, maximum temperature, average temperature, and minimum temperature were negatively associated with COVID-19-confirmed cases. These study findings build up knowledge pertaining the association between important meteorological factors and COVID-19 spread in various regions with different climates. The research outcomes could be helpful in understanding, bringing awareness, and educating Malaysian citizens through communication between citizens and governmental as well as non-governmental agencies via official portals to develop a better response mechanism for the Malaysian perspective.

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1 Introduction

Historically, pathogens have induced calamitous consequences in economies and social well-being (Briz-Redón & Serrano-Aroca, 2020). COVID-19 is a prominent example of a catastrophe that has brought human civilisations to a standstill (Rahman

& Kuddus, 2021). On 31 December 2019, the first outbreak of COVID-19 was announced in Wuhan Province, China (Suhaimi et al., 2020). The disease began as a collection of pneumonia cases with uncertain origin by late 2019. Subsequently, Severe Acute Respiratory Syndrome CoronaVirus-2 (SARS-CoV-2), a novel coronavirus, was responsible for the pneumonia cases (Zheng, 2020). The disease spread quickly worldwide, and COVID-19 was characterised and declared a pandemic by the World Health Organization on 11 March 2020 (Director-General's, 2020).

Based on the emerging epidemiological and laboratory evidence, suggestions were made that the COVID-19 pandemic may be affected by environmental conditions (Brassey et al., 2020). The suggestion is further supported by other studies that showed environmental conditions impacted the survival and spread of viruses such as Severe Acute Respiratory Syndrome (SARS) and influenza viruses that caused respiratory illnesses (Tamerius et al., 2013) (Rahman & Kuddus, 2021; Abdulla et al., 2021). In addition, tropical climates enable more frequent outdoor human interactions; hence, such regions are ideal for research regarding the natural spread of the virus (Prata et al., 2021).

Researchers in several ASEAN countries with tropical weather have studied various associations of COVID-19 spread with meteorological factors. For example, a study in Singapore revealed significant positive correlations between relative humidity, absolute humidity, temperature, water vapour, and dew point with the COVID-19 cases (Pani et al., 2020). Another study in Jakarta province, Indonesia, found that among weather components of humidity, maximum temperature, average temperature, and amount of rainfall, the merely average temperature had a significant and positive association with the COVID-19 pandemic (Tosepu et al., 2020). Moreover, a study in Kuala Lumpur City, Malaysia, explored the effects of meteorological parameters and air quality on the spread of SARS-CoV-2 (Suhaimi et al., 2020). In this study, relative humidity was found to have a positive association with daily COVID-19 case counts, whereas ambient temperature has a significantly negative association with daily COVID-19 cases. Nevertheless, an insignificant correlation was found between wind speed and COVID-19 transmission. A similar study in tropical Brazil found

that temperature, wind speed, and solar radiation exhibited a significant but negative correlation with COVID-19 incidence in Rio de Janeiro state, Brazil (Rosario et al., 2020).

However, characterising precise local humidity and temperature minimises that COVID-19 transmission is practically impossible (Araujo & Naimi, 2020). On the contrary, finding out the macroclimate conditions at locations where viral spread occurs is reasonable. For instance, the climate suitability for COVID-19 transmission is more difficult in tropical areas where high humidity and temperature typify the weather. A hypothesis was discussed by Bukhari and Jameel (2020) that the lower COVID-19 case counts were discovered within the tropics. Limited local viral spread, indicated by low case counts, was discovered at the start of the COVID-19 pandemic, especially in the equatorial countries within Southern Hemisphere, such as Indonesia, which could be attributed to inadequate testing (Indonesia, 2020). Furthermore, less mass testing occurs in many underdeveloped countries due to healthcare system deficiency, leading to lower case counts detected as inadequate testing was done to reveal the actual COVID-19 spread (Kaye et al., 2021).

Additionally, data of confirmed cases may have limitations due to variations in testing and reporting around the world due to problems with the availability of testing. The accuracy of tests may have induced high discrepancies between test-confirmed cases and the actual cases. Furthermore, other confounding variables such as population migration (Jia et al., 2020), social isolation strategies (Rahman et al., 2021, 2023), socioeconomic development (Qiu et al., 2020), cultural aspects (Borg, 2014; Gaygisiz et al., 2017; Huynh, 2020), public health policies on the surveillance and containment (Rahman et al., 2023) as well as population density (Kaye et al., 2021) (Kuddus & Rahman, 2021; Wong et al., 2023) could influence COVID-19 transmission throughout the globe. Even though knowledge from studies carried out by other countries can be utilised as a basis for the formulation of policy in general (Rahman et al., 2021), country-specific and state-wise studies are necessary as the meteorological characteristics and COVID-19 spread vary from country to country and state to state due to differences in climates.

The literature findings suggest that meteorological components, including humidity, temperature, and

wind speed, could significantly impact COVID-19 transmission, especially humidity and temperature. Nevertheless, the evidence that wind speed may have contributed to COVID-19 spread could have been more consistent among studies (Abdelhafez et al., 2021; Makama & Lim, 2021; Tan et al., 2021) as there are limitations in available data. In the context of Malaysia, there is a limited information whereby most of the existing studies focused primarily on Kuala Lumpur City (Makama & Lim, 2021; Suhaimi et al., 2020) but no other states in Malaysia, except for a study conducted by Tan et al., (2021) demonstrated that the correlation between seven weather variables and COVID-19 cases at the country level using Spearman's correlation test. However, the study period of Tan et al., (2021) research spanned only approximately 1 month (17 March to 30 April 2020). Furthermore, the rise of COVID-19 cases in March 2020 is primarily due to a 'Tabligh' gathering in the Seri Petaling Mosque (Shah et al., 2020). Therefore, the events mentioned above on COVID-19 cases had a more pronounced impact on COVID-19 cases than environmental factors in a short-term study. Hence, a crucial consideration for future research is the availability of more extended data sets (more than three months), as it is easier to assess the climate patterns with a higher analysis period. Therefore, further analysis of the COVID-19 pandemic is necessary to understand the effect of environmental factors on COVID-19 transmission and develop better warning systems that can predict future outbreaks and how this can inform infection control methods and public health measures.

This study aims to investigate the potential roles of meteorological parameters (average relative humidity, maximum temperature, average temperature, minimum temperature, and average wind speed) on COVID-19 spread in each of the 13 states of Malaysia using Spearman's and Pearson's correlation tests. The study considers more recent data over 8 months (i.e. 1 August 2020 to 31 March 2021). Our study outcomes could be helpful in understanding, bringing awareness, and educating the Malaysian and ASEAN citizens by communication between the citizens and governmental as well as non-governmental agencies via official portals to develop a better response mechanism.

2 Materials and methods

2.1 A brief about the climate of Malaysia

Malaysia comprises 13 states (Perlis, Kedah, Pulau Pinang, Perak, Selangor, Negeri Sembilan, Melaka, Johor, Pahang, Terengganu, Kelantan, Sabah, and Sarawak) and three federal territories (Kuala Lumpur, Putrajaya, and Labuan). It is one of the South-east Asian countries in the tropical region characterised by a hot and humid climate for most of the year (Dotse et al., 2016). The country is subject to maritime influence and the interplay of wind systems from the South China Sea and the Indian Ocean. Moreover, Malaysia faces two monsoon seasons which are the north-east monsoon (from November to March) and the south-west monsoon (from late May to September) (Safiah Yusmah et al., 2020). The north-east monsoon usually carries heavy rainfall, which frequently induces widespread floods in the east coast states in Peninsular Malaysia, including Kelantan, Pahang, and Terengganu (Safiah Yusmah et al., 2020). The effects mentioned above of monsoon also occur in Sabah and Sarawak. In contrast, relatively drier weather is expected for the west coast states, particularly Johor, Kedah, Perak, and Selangor, when the south-west monsoon arrives in Malaysia (Safiah Yusmah et al., 2020). Windstorm strikes are frequent in the country during the monsoon transition phase (October and April) (Chik et al., 2019).

State-wise data were considered for this study as previous studies only utilised data at the city level in Malaysia (Makama & Lim, 2021; Suhaimi et al., 2020). At most, one representative meteorological station was selected for each state in Malaysia. The meteorological data were measured via the 13 meteorological stations of all 13 states. The name of the study area and the location in the form of latitude and longitude for all meteorological stations are summarised in Table SI 1.

2.2 Variables selection and data collection

The dependent variable of daily new COVID-19-confirmed cases was considered for 212 days from 1 August 2020 to 31 March 2021, which were gathered at the state level from the official website of the Ministry of Health Malaysia via <http://covid-19.moh.gov.my>.

gov.my/terkini. Initially, 15 March 2020 was used as the commencement date for the study period. However, many reported meteorological data were absent between 15 March 2020 and 29 July 2021 for both Perlis and Kedah states. Therefore, 1 August 2020 was utilised as the starting date of the study period.

The independent variables of daily records of state-wise meteorological variables, including average relative humidity (RH_{avg}) (%), maximum temperature (T_{max}) (°C), average temperature (T_{avg}) (°C), minimum temperature (T_{min}) (°C), and average wind speed (WS_{avg}) (m/s), were collected from the Malaysian Meteorological Department (Jalan Sultan, Bandar Baru Petaling Jaya, 46,667 Petaling Jaya, Selangor). Table 1 shows the descriptions for meteorological variables. As the magnitude of meteorological variables fluctuates slightly throughout the day, daily average measurements were used. The utilisation of daily average measurements of meteorological variables is aligned with previous studies (Pani et al., 2020; Rosario et al., 2020; Suhaimi et al., 2020).

2.3 Statistical analysis

Statistical analysis was applied to assess the relationship between the independent variables, which are the five meteorological variables (RH_{avg} , T_{max} , T_{avg} , T_{min} , and WS_{avg}) and the dependent variable (daily COVID-19-confirmed cases). Firstly, the normality of all data was assessed using a graphical method, the Quantile–Quantile (Q–Q) plot. For continuous data in this study, normality check is important as selection of parametric or non-parametric tests is decided based on the status of normality (Mishra et al., 2019). Then, Pearson’s (parametric) and Spearman’s (non-parametric) correlation tests were utilised to explore the association between meteorological variables and COVID-19 spread with the data that fulfilled and violated the normality assumption, respectively. The benchmark of correlation strength utilised in this study followed by the most commonly used

interpretation of the correlation value (r -value) for medical science (Chan, 2003). Null and alternative hypotheses were established; null hypothesis states that population correlation coefficient equals to 0 (no linear relationship in the population) whereas alternative hypothesis states that correlation coefficient does not equal to 0 (more than or less than zero, with linear relationship in the population). Next, the values of test statistics for both Pearson’s and Spearman’s correlation coefficient were calculated using the formula:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$$

Then, the resulting test statistics were utilised to calculate probability value (p -value). Statistical significance was set at p -value < 0.05 and 95% CI in a two-tailed fashion. Null hypothesis was rejected when p -value was smaller than 0.05; therefore, a conclusion can be made that there is enough evidence at 0.05 level to conclude a linear association which exists between a daily meteorological parameter and daily COVID-19-confirmed cases. Conversely, null hypothesis was failed to be rejected when p -value was greater than 0.05; therefore, a conclusion can be made that there is insufficient evidence at 0.05 level to conclude a linear association which exists between a daily meteorological parameter and daily COVID-19-confirmed cases. The IBM Statistical Package for the Social Sciences (SPSS) (version 27) software was used for all statistical analyses. Figure 1 illustrates the stages involved in conducting the research.

3 Results

3.1 Summary statistics of meteorological variables

As shown in Table 2, a descriptive overview of the meteorological data indicates that daily RH_{avg} ranged from 45.7% in Pulau Pinang to 98.3% in

Table 1 Definitions for meteorological variables investigated by this study

Meteorological variable	Description
RH	Highest water content that air could bear at a given temperature
T	Temperature of ambient air at the earth’s surface
WS	Speed at which air flows around pressure systems from high to low or due to temperature variations

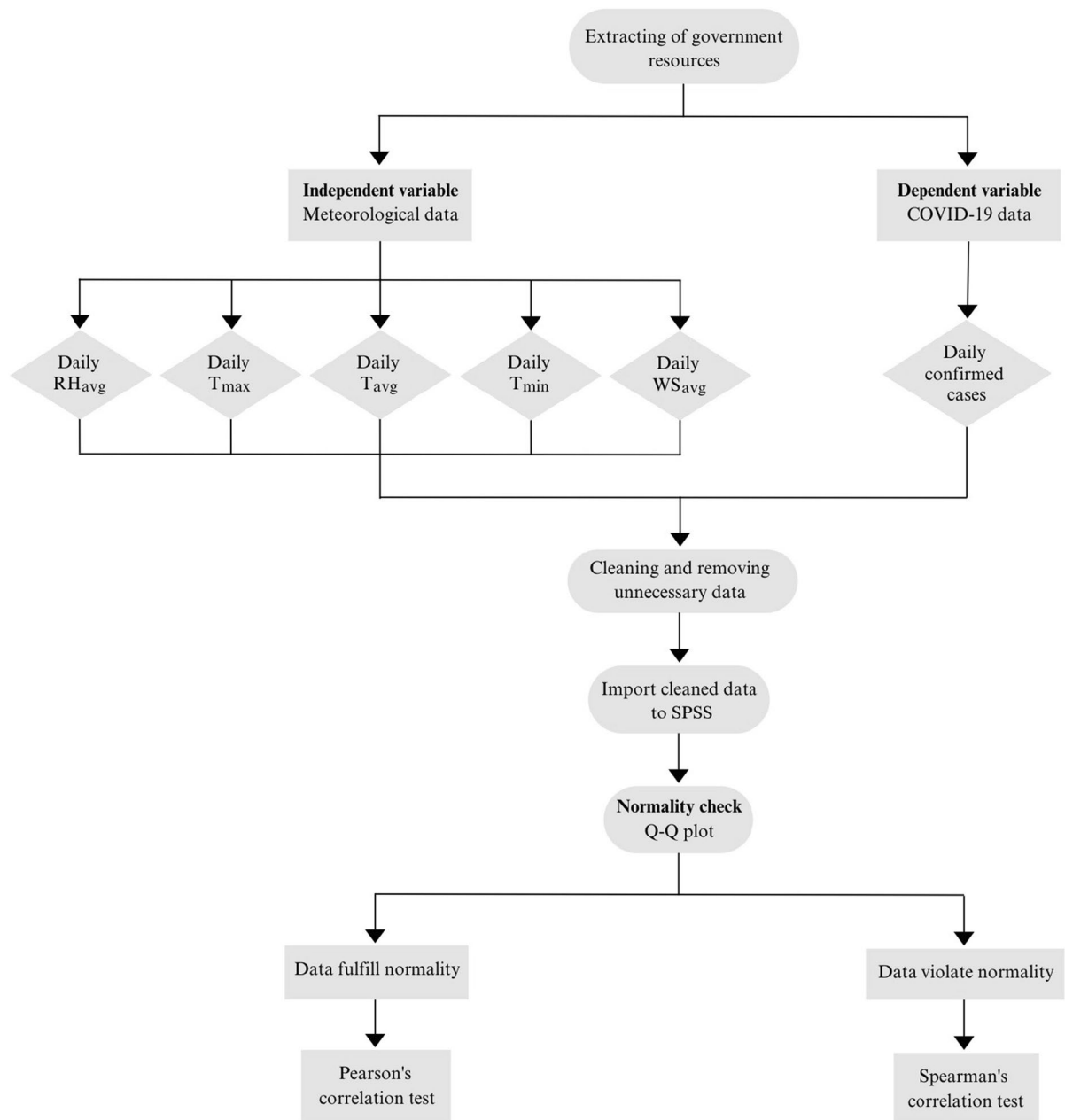


Fig. 1 Flowchart of the research framework for this study

Kedah, with a mean of 81.1% across all states. Furthermore, the range of daily T_{\max} was 23.1 °C in Sabah to 37.4 °C in Kedah, with a mean of 31.8 °C. In addition, the highest T_{avg} of 31.1 °C was recorded in Selangor, and the lowest T_{avg} of 22.0 °C was recorded in Sabah, with a mean of 27.1 °C across all states. Furthermore, the highest T_{\min} of 27.8 °C was

recorded in Pulau Pinang, whereas the lowest T_{\min} of 19.8 °C was recorded in both Perlis and Kedah, with a mean of 24.0 °C. Lastly, Terengganu had the highest WS_{avg} , which was 6.2 m/s, whereas the minimum WS_{avg} recorded was in Perlis (0.4 m/s), with a mean of 1.8 m/s.

Table 2 Summary statistics of meteorological variables for 13 states of Malaysia

Meteorological variable	Mean	Standard deviation	Maximum	Minimum
Daily RH_{avg} (%)	81.1	7.2	98.3	45.7
Daily T_{max} (°C)	31.8	1.9	37.4	23.1
Daily T_{avg} (°C)	27.1	1.2	31.1	22.0
Daily T_{min} (°C)	24.0	1.1	27.8	19.8
Daily WS_{avg} (m/s)	1.8	0.7	6.2	0.4

3.2 State-wise daily COVID-19 case counts with meteorological variables

Figure 2 illustrates the COVID-19-confirmed cases and meteorological changes per day in each of the 13 states in Malaysia throughout the studied period (from 1 August 2020 to 31 March 2021). The trends of the daily number of confirmed cases over time varied across the states. For example, in October 2020, the number of COVID-19-confirmed cases soared exponentially in Sabah compared to other states. The highest number of confirmed cases recorded during the studied period was 1199 on 6 November 2020. Other states, such as Selangor, Kedah, and Pulau Pinang, also increased in daily confirmed cases starting from October 2020.

In Perlis, the daily confirmed cases were generally low throughout the studied period, as the highest daily confirmed cases reported between 1 August 2020 and 15 January 2021 were 10 confirmed cases (reported on 7 August 2020). In Perak, the daily confirmed cases started to rise around November 2020, with a modest, increasing trend of daily confirmed cases observed over time. The estimate suddenly peaked at 1215 confirmed cases on 21 February 2021. In Negeri Sembilan, daily confirmed cases were higher around 22 October 2020 compared to previous days.

For Melaka, the rise of daily confirmed cases commenced around December 2020 and peaked at 344 confirmed cases on 8 February 2021. After reaching the peak, the daily confirmed cases in Melaka decreased. In Johor, the daily confirmed cases rose by November 2020, peaked at 1069 cases on 27 January 2021, and decreased throughout February and March 2021. In Pahang, low daily confirmed cases (with zero cases on most days) were reported from 1 August to the end of November 2020. In Kelantan,

zero cases were reported between 1 August and 22 September 2020. After that, the daily confirmed cases rose and reached the second-highest peak (161 cases) on 22 January 2021.

In Terengganu and Sarawak, daily confirmed cases surged by the beginning of January. Judged by the trends of daily confirmed cases, the outbreaks in 13 states that induced the rise of daily confirmed cases were agitated over a certain period, especially during the late months of the studied period.

3.3 Results of normality check

Table 3 shows the normality check results derived from Q–Q plots in Fig. SI 2–78. The normality assumption was violated for data of the dependent variable (daily COVID-19-confirmed cases) for Perlis, Kedah, Melaka, Johor, Terengganu, and Sarawak, except for Pulau Pinang, Perak, Selangor, Negeri Sembilan, Pahang, Kelantan, and Sabah. In addition, the data of an independent variable and the daily WS_{avg} for both Terengganu and Kelantan states also violated the normality assumption. Conversely, the independent variables (daily RH_{avg} , daily T_{max} , daily T_{avg} , and daily T_{min}) for all Malaysian states fulfilled the normality assumption. Lastly, Fig. 3 illustrates the result of normality check using overall data of each variable that spanned from the period between 1 August 2020 and 31 March 2021 in the entire Malaysia.

3.4 Results of correlation analysis

Pearson's and Spearman's correlation tests were utilised for the independent and dependent variables in various states depending on the normality test results. Correlation test results are shown in Table 4. In Pahang and Sarawak, daily RH_{avg} was insignificantly correlated with COVID-19 case counts as p -value > 0.05. In other states, daily RH_{avg} had significant correlations with COVID-19 case counts (p -value < 0.05). The daily COVID-19-confirmed cases had somewhat negative correlations with RH_{avg} in Perlis, Kedah, Pulau Pinang, Perak, Terengganu, and Kelantan; weakly negative correlations with RH_{avg} in Selangor, Melaka, and Johor. Only in Negeri Sembilan and Sabah, where the daily COVID-19-confirmed cases had weakly positive correlations with RH_{avg} . With adequate strength, Kedah and Pulau

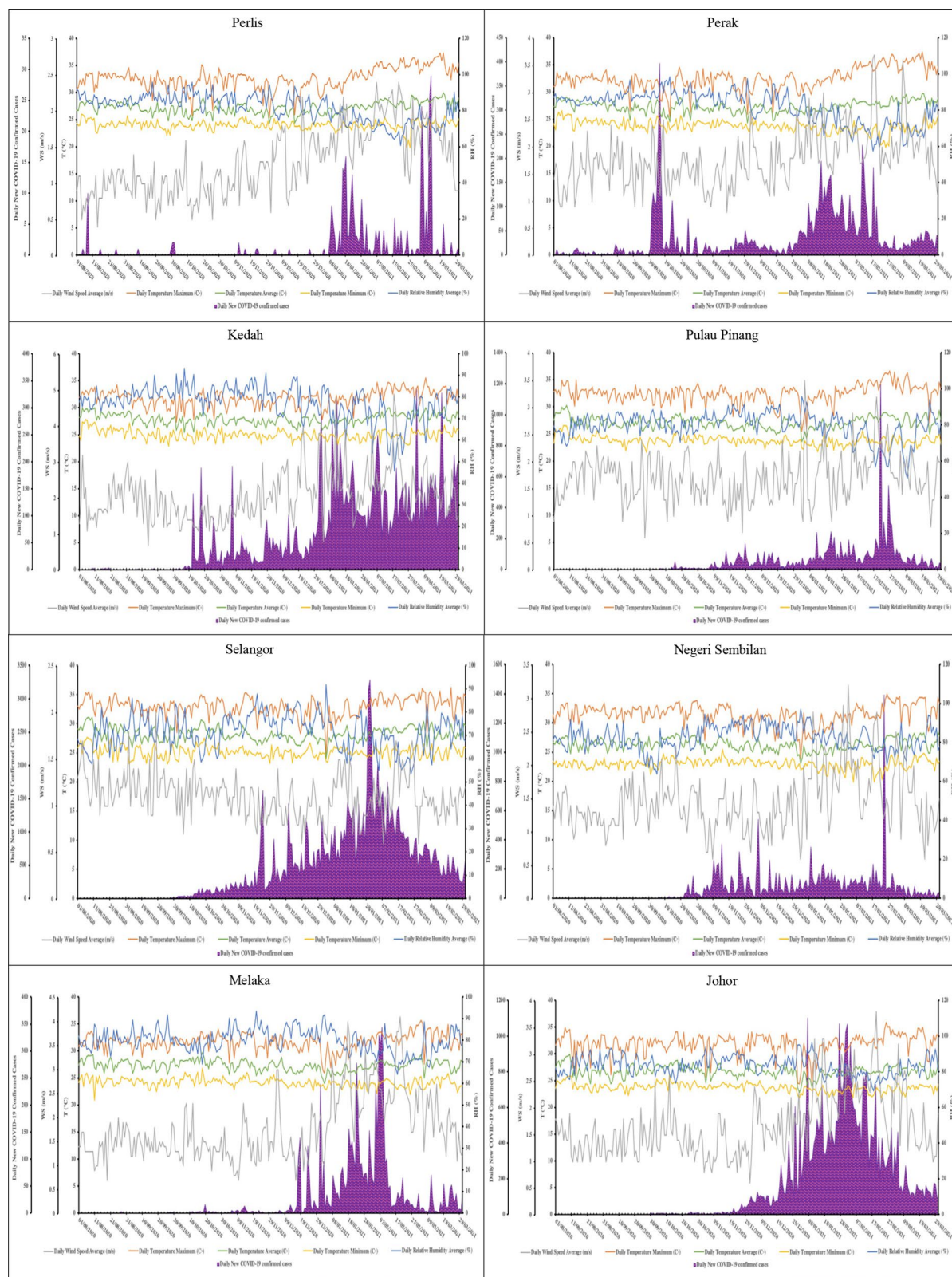


Fig. 2 Daily changes of meteorological parameters and COVID-19-confirmed cases for remaining seven states (Perlis, Perak, Kedah, Pulau Pinang, Selangor, Negeri Sembilan, Melaka, Johor, Pahang, Terengganu, Kelantan, Sabah, and

Sarawak) of Malaysia. [The purple areas signify the daily number of confirmed cases. The coloured lines signify the meteorological variations over time]

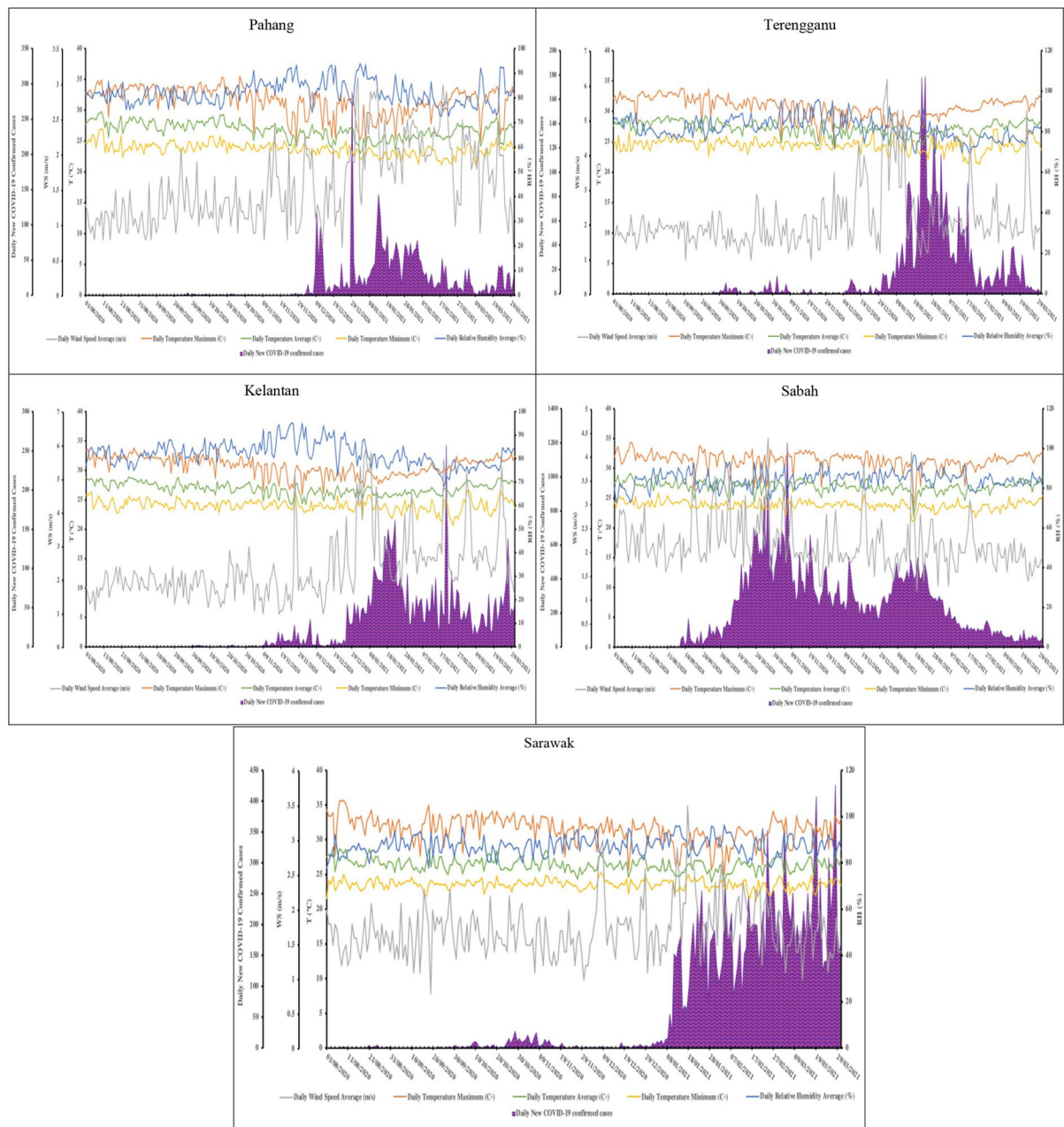


Fig. 2 (continued)

Pinang had the highest significant negative association ($r = -0.439$ and $r = -0.440$, respectively). In contrast, Sabah had the highest significant positive correlation ($r = 0.175$) with poor strength between daily RH_{avg} and confirmed COVID-19 cases.

In Selangor, Melaka, and Johor, daily T_{max} had insignificant associations with

COVID-19-confirmed cases ($p\text{-value} > 0.05$). Nevertheless, the daily COVID-19 confirmed cases had pretty negative associations with T_{max} in Pahang, Terengganu, and Kelantan; weakly negative correlations between daily T_{max} and COVID-19 case counts in Negeri Sembilan, Sabah, and Sarawak. The daily COVID-19 case counts had weakly

Table 3 Normality assumptions of daily COVID-19 case counts and each meteorological variables for each of the 13 states of Malaysia

State	Meteorological parameter					
	Daily COVID-19-con- firmed cases	Daily RH_{avg}	Daily T_{max}	Daily T_{avg}	Daily T_{min}	Daily WS_{avg}
Perlis	×	✓	✓	✓	✓	✓
Kedah	×	✓	✓	✓	✓	✓
Pulau Pinang	✓	✓	✓	✓	✓	✓
Perak	✓	✓	✓	✓	✓	✓
Selangor	✓	✓	✓	✓	✓	✓
Negeri Sembilan	✓	✓	✓	✓	✓	✓
Melaka	×	✓	✓	✓	✓	✓
Johor	×	✓	✓	✓	✓	✓
Pahang	✓	✓	✓	✓	✓	✓
Terengganu	×	✓	✓	✓	✓	×
Kelantan	✓	✓	✓	✓	✓	×
Sabah	✓	✓	✓	✓	✓	✓
Sarawak	×	✓	✓	✓	✓	✓

[The boxes with cross symbol denote that the normality assumption of data for variables was violated. In contrast, the boxes with ticks denote that the normality assumption of data for variables was fulfilled]

positive correlations with T_{max} in Perlis, Kedah, Pulau pinang, and Perak. Terengganu had the highest significant negative association with adequate strength ($r = -0.440$). Despite the poor correlation strength, Pulau Pinang had the highest significant positive correlation ($r = 0.241$) between daily RH_{avg} and COVID-19-confirmed cases.

In Kedah, Pulau Pinang, Perak, and Selangor, daily T_{avg} was insignificantly correlated to COVID-19-confirmed cases ($p\text{-value} > 0.05$). The daily COVID-19-confirmed cases had negative associations with T_{avg} in Pahang and Terengganu; weakly negative associations with T_{avg} in Negeri Sembilan, Melaka, Johor, Kelantan, Sabah, and Sarawak. Whereas positive correlations between the daily confirmed cases and T_{avg} were only found in Perlis, Pulau Pinang, and Perak, the strength of the correlations was all poor. Pahang had the highest significant negative correlation ($r = -0.375$) with adequate strength, whereas Perlis had the highest significant positive correlation ($r = 0.180$) between daily RH_{avg} and COVID-19-confirmed cases.

In Perlis, Pulau Pinang, Selangor, and Sarawak, daily T_{min} had insignificant correlations with COVID-19 case counts ($p\text{-value} > 0.05$). The daily COVID-19 case counts had negative and significant

correlations ($p\text{-value} < 0.05$) with T_{min} in Kedah, Johor, and Pahang; weak significant negative correlations with T_{min} in Perak, Negeri Sembilan, Melaka, Terengganu, Kelantan, and Sabah. Johor showed the highest significant but weak negative correlation ($r = -0.415$) between daily RH_{avg} and confirmed COVID-19 cases. No positive correlation was found between daily T_{min} and COVID-19-confirmed cases in any state.

In Negeri Sembilan and Sabah, daily WS_{avg} was insignificantly correlated with COVID-19 case counts ($p\text{-value} > 0.05$). The daily WS_{avg} had weak positive correlations with COVID-19 case counts in Perak, Terengganu, and Sarawak; fairly positive significant correlation with COVID-19 case counts in Perlis, Kedah, Pulau Pinang, Melaka, Johor, Pahang, and Kelantan. A significant negative association was revealed between daily WS_{avg} and COVID-19-confirmed cases in only Selangor, although the correlation was weak ($r = -0.170$). Of 10 states with significant positive correlations between daily WS_{avg} and confirmed COVID-19 cases, Kelantan showed the highest significant positive correlation ($r = 0.569$).

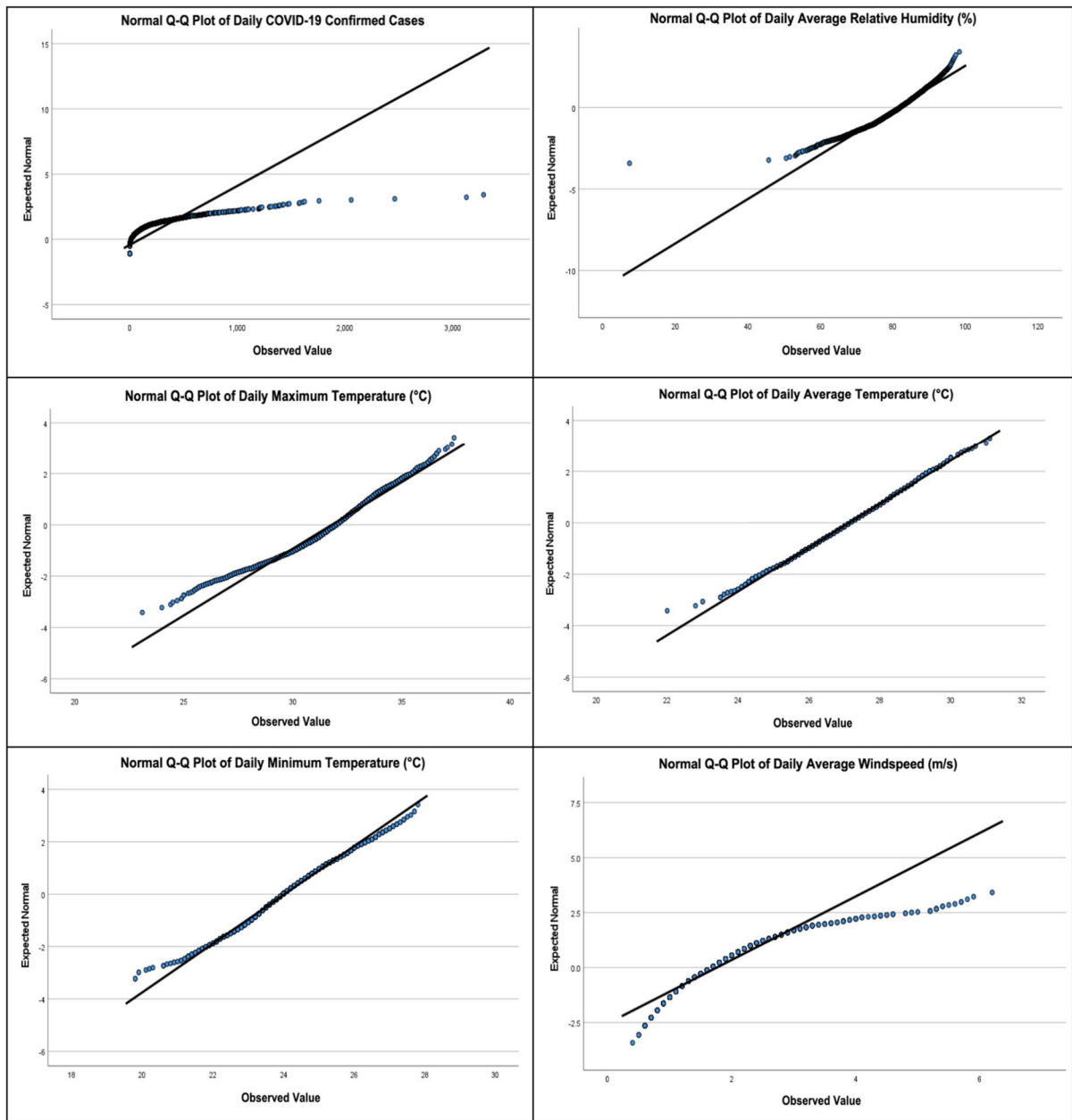


Fig. 3 Overall normal Q–Q plots of daily COVID-19-confirmed cases and daily meteorological data in the entire Malaysia

3.5 Overall correlation

The overall correlation between each meteorological variable and daily COVID-19-confirmed cases within Malaysia was generated to assess the overall

association of COVID-19 cases with meteorological changes in Malaysia. Spearman's correlation was obtained from all variables because the dependent variable (daily COVID-19 case counts) violated the normality assumption as determined by the Q–Q plot. Overall, a weak but significant association (p -value < 0.05) exists between daily COVID-19

Table 4 Results of correlation test for 13 states of Malaysia

State		Meteorological parameter				
		Daily RH_{avg}	Daily T_{max}	Daily T_{avg}	Daily T_{min}	Daily WS_{avg}
Perlis	Daily COVID-19-confirmed cases	−0.386 ^{s,*}	0.227 ^{s,*}	0.180 ^{s,*}	−0.026 ^s	0.334 ^{s,*}
Kedah		−0.439 ^{s,*}	0.151 ^{s,*}	−0.015 ^s	−0.334 ^{s,*}	0.406 ^{s,*}
Pulau Pinang		−0.440 ^{p,*}	0.241 ^{p,*}	0.119 ^p	−0.093 ^p	0.379 ^{p,*}
Perak		−0.316 ^{p,*}	0.172 ^{p,*}	0.068 ^p	−0.219 ^{p,*}	0.210 ^{p,*}
Selangor		−0.138 ^{p,*}	0.016 ^p	−0.101 ^p	−0.121 ^p	−0.170 ^{p,*}
Negeri Sembilan		0.139 ^{p,*}	−0.148 ^{p,*}	−0.158 ^{p,*}	−0.135 ^{p,*}	0.066 ^p
Melaka		−0.190 ^{s,*}	0.061 ^s	−0.268 ^{s,*}	−0.294 ^{s,*}	0.513 ^{s,*}
Johor		−0.258 ^{s,*}	0.004 ^s	−0.183 ^{s,*}	−0.415 ^{s,*}	0.556 ^{s,*}
Pahang		−0.009 ^p	−0.321 ^{p,*}	−0.375 ^{p,*}	−0.334 ^{p,*}	0.430 ^{p,*}
Terengganu		−0.379 ^{s,*}	−0.440 ^{s,*}	−0.368 ^{s,*}	−0.206 ^{s,*}	0.235 ^{s,*}
Kelantan		−0.366 ^{p,*}	−0.320 ^{p,*}	−0.259 ^{p,*}	−0.197 ^{p,*}	0.569 ^{s,*}
Sabah		0.175 ^{p,*}	−0.195 ^{p,*}	−0.232 ^{p,*}	−0.205 ^{p,*}	0.073 ^p
Sarawak		0.001 ^s	−0.256 ^{s,*}	−0.128 ^{s,*}	−0.076 ^s	0.169 ^{s,*}

^sCorrelation is quantified via Spearman's correlation coefficient

^pCorrelation is quantified via Pearson's correlation coefficient

*Correlation is significant at p -value < 0.05

Table 5 Overall Spearman's correlation between each meteorological variable and daily COVID-19-confirmed cases in Malaysia

Meteorological variable	Spearman's correlation
Daily RH_{avg}	−0.147*
Daily T_{max}	−0.071*
Daily T_{avg}	−0.104*
Daily T_{min}	−0.120*
Daily WS_{avg}	0.218*

*Correlation is significant at p -value < 0.05

case counts and all meteorological variables within Malaysia. Daily COVID-19-confirmed cases within the country were negatively associated with four meteorological variables, including daily RH_{avg} , T_{max} , T_{avg} , and T_{min} . On the other hand, merely daily WS_{avg} was correlated positively with daily COVID-19 case counts, as shown in Table 5.

4 Discussion

4.1 Relative humidity and COVID-19

According to summary statistics in Table 2, the mean for daily RH_{avg} in 13 states was 81.1%; the highest RH_{avg} was recorded in Kedah (98.3%), whereas the lowest RH_{avg} (45.7%) was recorded in Pulau Pinang. The variations in RH across all states could be attributed to the difference in latitudes and longitudes of the areas. Based on the results in Table 4, daily RH_{avg} in most states (9 out of 13) showed a negative association with daily confirmed cases. The overall correlation between daily RH_{avg} and COVID-19-confirmed cases of all states was significantly negative, although poor correlation ($r = -0.147$) is shown in Table 5. According to Fig. 2, there were pronounced changes in RH starting from December 2020 in most meteorological stations. It could be related to seasonal changes from the south-west to the north-east monsoon. As discussed earlier, relatively drier weather is expected for Kedah, Perak, and Selangor during the north-east monsoon (November–March), which is undoubtedly followed by reduced RH . At the same time, the daily number of COVID-19 cases increased sharply in most states. The statistical relationship, thus, shows a significant negative correlation.

However, considering the latest condition, Malaysia's second wave (May 2021) and third wave of COVID-19 (August to September 2021) occurred during different seasons.

A study by Biryukov et al. (2020) explored the survival rates of SARS-CoV-2 on various surface types and found that SARS-CoV-2 had a shorter half-life under the influence of high *RH* and *T*. Hence, they concluded that either increase in *RH* or *T* increases rate of the virus decay. Other statistical modelling studies also found that a higher *RH* could lead to lowering COVID-19-confirmed cases (Ma et al., 2020; Zhao et al., 2020) which is in line with the findings of this study. An analysis from 166 countries conducted by Wu et al. (2020) showed that a 1% rise in *RH* could lead to a 0.85% decrease in daily confirmed cases, substantially lowering COVID-19 transmission. Moreover, Ward et al. (2020) carried out a study in Sydney, Australia, amidst the early stage of the COVID-19 epidemic and found that a 1% decrease in humidity could lead to a 6% rise in the number of COVID-19-confirmed cases, which indicates that COVID-19 could be a seasonal illness with greater risk during winter. Furthermore, Chan et al. (2011) found that tropical countries such as Indonesia, Malaysia, and Thailand have no major community outbreaks of SARS-CoV-1, which might be due to the viability of the virus that was lost quickly at higher *RH* along with higher *T*. It is further supported by a study done in Bangladesh whereby the spread of COVID-19 was found to be mitigated by high *RH* within tropical regions (Haque & Rahman, 2020). Other than that, the mechanisms concerning the effects of humidity on human immunity can also explain why higher *RH* lowers the probability of hosts being infected by COVID-19.

A primary defence mechanism, Mucociliary clearance (MCC), also removes inhaled pathogens and irritants from respiratory epithelial surfaces. Healthy airways are covered with cilia that line along the respiratory airways covered by a mucus layer that traps foreign pathogens and a low viscosity periciliary layer that lubricates the airway which facilitates beating of cilia for efficient mucus clearance via expectoration (Knowles & Boucher, 2002). Research conducted by Kudo et al. (2019) found that mice are more susceptible to influenza infection after incubating the mice to low *RH* (20%) in comparison with high *RH* (50%).

They found that the dry air impairs the host's defence against the infection by disrupting the effective operation of cilia, which removes pathogens and pollutants, reduces lung tissue repair, and disrupts the cell signalling mechanism crucial in alerting the immune system about the invasion of the virus. Inhalation of cold air, which is always dry due to limited water-holding capacity, could impair MCC (Moriyama et al., 2020). Therefore, high *RH* might benefit the human respiratory tract in combating foreign pathogens such as viruses as humid air humidifies the respiratory tract by enhancing lubrication, which is part of the respiratory tract's mechanism in clearing unclean air upon reaching the alveolar for perfusion.

Moreover, large-sized droplets coughed by infectors can only travel a limited distance before dropping to the ground due to the downward pulling effect of gravity (Zhao et al., 2020). Therefore, higher *RH* might prevent the droplets from rapid evaporation to form aerosol particles that can travel further and persist in the air longer (Božič & Kanduč, 2021). This could explain the rise of daily COVID-19 case counts in Pulau Pinang in February, as the *RH* in the state was significantly lower during that period, with the lowest *RH* (45.7%) recorded among all states. Nevertheless, the study executed by Suhaimi et al. (2020) demonstrated contradicting finding with this study whereby *RH* positively correlated to daily COVID-19 case counts in Malaysia. Furthermore, they found that the virus could survive for more extended periods in the condition of high outdoor humidity in tropical countries. Auler et al. (2020) also had similar findings whereby COVID-19 spread in Brazil was favoured by high *RH* (near 80%).

4.2 Temperature and COVID-19

Approximately half of the total number of states involved in a positive correlation between daily T_{\max} and COVID-19 case counts; the other half engaged in negative association. The overall correlation ($r = -0.071$; $p\text{-value} < 0.05$) between these two variables shows that the higher the T_{\max} , the more likely the COVID-19 spread would be limited. This finding aligns with the observation from a previous study (Rosario et al., 2020). However, some studies show contradicting results with this study whereby higher daily COVID-19 case counts correlate with higher T_{\max} (Abdelhafez et al., 2021; Singh et al.,

2005; Tosepu et al., 2020). T_{avg} and T_{min} had a significant negative correlation with daily COVID-19 case counts for most of the states. COVID-19 spread is more at risk between 24 °C and 29 °C, but the risk dramatically reduces when T exceeds 29 °C (Aidoo et al., 2021). High T induces disintegration of the lipid layer of the virus that reduces its stability and viral infection potential, which could lead to virus inactivation, thereby decreasing the virus transmission rate (de Ángel Solá et al., 2020; Moriyama et al., 2020).

Moreover, high T could be associated with reducing the activeness of viruses and their biological interactions with humans (Gardner et al., 2019). Compared to other organisms, viruses do not have hardened protective tissues as they have a simple structure composed of a protein coat and genetic materials within the coat (Yang et al., 2021). Riddell et al. (2020) demonstrated the rise in T while maintaining RH at 50% significantly reduced SARS-CoV-2 viability from 28 days (20 °C) to 7 days (30 °C), following as little as 24 h at 40 °C. Nevertheless, insignificant associations were revealed between daily T_{max} and COVID-19 case counts in Selangor, Melaka, and Johor. This could be due to confounding variables such as the high population density in Selangor, Melaka, and Johor compared to relatively lower population density in Pahang, Terengganu, and Kelantan. Previous research shows that a positive association exists between infection of COVID-19 and population density, as the residents living in highly populated areas have a much greater probability of coming into close contact with other residents (Sharif et al., 2022b).

4.3 Wind speed and COVID-19

Based on the overall correlation test, it was noticed that the only meteorological variable that had a significant positive trend with daily COVID-19 case counts was WS . Moreover, the daily WS_{avg} was positively correlated with all states except for Selangor, as shown in Table 4. Table 5 shows the overall correlation between daily COVID-19 case counts and WS_{avg} ($r=0.218$; $p\text{-value}<0.05$). The positive r -value denotes that daily COVID-19 case counts increased with the increase in WS_{avg} , although the correlation was poor. As a whole, Malaysia faces low WS , although stronger WS can occur during the early and

late months of every year. Besides, WS varies across different areas in Malaysia. There was an overall increasing trend of daily WS_{avg} over the studied period in Terengganu and Kelantan. In Peninsular Malaysia, towns along the east coast, including Kota Bharu and Kuala Terengganu, experience relatively stronger and faster winds than towns from other states. The finding of this study is similar to previous studies conducted within cities of Turkey (Şahin, 2020) and <https://www.mdpi.com/1660-4601/18/2/484> China (Yang et al., 2021). Şahin (2020) discovered that WS 14 days before the day that COVID-19-confirmed cases were recorded had a high impact on COVID-19 cases as the correlation was positive.

Moreover, Yang et al. (2021) found that the WS was positively associated (moderate strength and significant correlation) with case counts of COVID-19 in Beijing. Droplets of small size dry instantly to form a cloud of aerosol particles that will suspend for a considerable amount of time in the air. Therefore, aerosols released by infectors via sneezing and coughing could travel for a longer duration and further with the assistance of wind, which facilitates the viral spread from the infector to other persons (Peci et al., 2019). Nevertheless, the findings of this study contradict several studies (Abdelhafez et al., 2021; Rosario et al., 2020; Sharif et al., 2022a). In indoor and outdoor environments, a higher level of wind velocity reduces viral load by dispersion and dilution of the virus concentration in the air, decreasing SARS transmission (Cai et al., 2007; Coccia, 2021).

5 Conclusion

In this study, all the studied meteorological variables including daily RH_{avg} , T_{max} , T_{avg} , T_{min} , and WS_{avg} were significantly correlated with daily COVID-19-confirmed cases in 13 states of Malaysia. It was found that the risk of COVID-19 acquired from symptomatic and asymptomatic infectors within a community appears to be sensitive to meteorological conditions, as indicated by the significance of overall correlations. Nevertheless, the weak strengths of overall correlations suggest that although the studied meteorological factors indeed play a role in SARS-CoV-2 transmissibility, the factors are not the sole determinant for SARS-CoV-2 transmissibility. Besides meteorological factors, virus and host factors

could determine whether transmission occurs successfully (Akbar & Gilroy, 2020; Brandt & Mersha, 2021; Carabelli et al., 2023). Furthermore, previous studies showed that population migration (Jia et al., 2020), social isolation strategies, socioeconomic development (Qiu et al., 2020), cultural aspects (Borg, 2014; Gaygisiz et al., 2017; Huynh, 2020), public health policies on the surveillance (Rahman & Kuddus, 2021; Abdulla et al., 2021; Rahman et al., 2023), and containment (Kuddus & Rahman, 2021) as well as population density (Kaye et al., 2021) (Wong et al., 2023) could also influence COVID-19 transmission. Moreover, any contradicting results reported in the literature could be due to the differences in the study time range, analysis methods, and study regions or other variables.

The limitation of this study is that the collected meteorological data are absent for a certain period for specific states. So, to match the daily COVID-19 case counts and the daily meteorological data, the original duration of this study must be shortened from 8 to 12 months. Furthermore, the statistical analysis has not considered an exposure risk to SARS-CoV-2 or individual health factors such as personal hygiene. Future studies could address any limitations. Confounding factors such as population density should be considered in statistical analysis to minimise masking effect of the confounding factors on the meteorological variables of interest. Investigation of more meteorological and seasonal risk factors should be conducted in tropical settings, as this may further strengthen the evidence for environmental components of COVID-19 transmission. In addition, further studies with sufficient meteorological and epidemiological data generated over an extended period (for instance, more than a year) should be executed to determine whether there are any seasonal patterns of COVID-19.

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Author contributions MZH was conceived the project concept; KYN was cleaned the data and performed the data analysis; model development and interpretation under the supervision of MZH. KYN, and MZH wrote the initial draft of this

manuscript under the supervision of AR; AR was provided critical feedback to improve and complete the manuscript. All authors revised, and approved the final manuscript and submission for publication.

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Data availability The datasets used in this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval Open source data were used in this study.

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