RESEARCH ARTICLE

Interaction between meteorological parameters and COVID-19: an ecological study on 406 authorities of the UK

Mohammad Sarmadi[1,2] · Sajjad Rahimi[1,2] · Darrick Evensen[3] · Vahid Kazemi Moghaddam[4]

Abstract

Understanding the factors affecting COVID-19 transmission is critical in assessing and mitigating the spread of the pandemic. This study investigated the transmissibility and death distribution of COVID-19 and its association with meteorological parameters to study the propagation pattern of COVID-19 in UK regions. We used the reported case and death per capita rate (as of November 13, 2020; before mass vaccination) and long-term meteorological data (temperature, humidity, precipitation, wind speed, and visibility) in 406 UK local authority levels based on publicity available secondary data. We performed correlation and regression analysis between COVID-19 variables and meteorological parameters to find the association between COVID-19 and independent variables. Student's T and Mann–Whitney's tests were used to analyze data. The correlation and regression analyses revealed that temperature, dew point, wind speed, and humidity were the most important factors associated with spread and death of COVID-19 (P <0.05). COVID-19 cases negatively correlated with humidity in areas with high population density, but the inverse in low population density areas. Wind speeds in low visibility areas, which are considered polluted air, may increase the spread of disease (r=0.42, P <0.05) and decrease the spread in high visibility areas (r=−0.16, P <0.05). Among low (T <10°C) and high (T >10°C) temperature areas, the average incidence rates were 2056.86 (95% confidence interval (CI): 1909.49–2204.23) and 1446.76 (95% CI: 1296.71–1596.81). Also, COVID-19 death per capita rates were 81.55 (95% CI: 77.40–85.70) and 69.78 (95% CI: 64.39–75.16) respectively. According to the comprehensive analysis, the spread of disease will be suppressed as the weather warms and humidity and wind speed decrease. Different environmental conditions can increase or decrease spread of the disease due to affecting spread of disease vectors and by altering people's behavior.

Keywords COVID-19 · Environmental factors · Meteorological parameters · Temperature · Wind speed · Humidity

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Mohammad Sarmadi, Sajjad Rahimi, and Darrick Evensen have equal contributions.

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✉ Mohammad Sarmadi
    msarmadi2@gmail.com

✉ Darrick Evensen
    darrick.evensen@ed.ac.uk

[1] Department of Environmental Health Engineering, School of Health, Torbat Heydariyeh University of Medical Sciences, Torbat Heydariyeh, Iran

[2] Health Sciences Research Center, Torbat Heydariyeh University of Medical Sciences, Torbat Heydariyeh, Iran

[3] Department of Politics and International Relations, University of Edinburgh, Edinburgh EH89LF, UK

[4] Department of Environmental Health Engineering, Neyshabur University of Medical Sciences, Neyshabur, Iran

Introduction

The outbreak of the coronavirus disease 2019 (COVID-19) emerged in the city of Wuhan, Hubei Province, China, in December 2019, and then swiftly spread around the world within several months (Chen et al. 2020; Rubin et al. 2020). Before this pandemic, the Middle East respiratory syndrome coronavirus (MERS-CoV) and severe acute respiratory syndrome coronavirus (SARS-CoV) had brought tensions to societies but in low pressure (Wu et al. 2020a). The COVID-19 pandemic has affected a total number of 110,763,898 persons globally, involving more than 220 countries and territories and resulted in a cumulative of 2,455,331 deaths worldwide as of 21 February 2021 (WHO 2021). During the pandemic, remarkable research was widely conducted on the factors affecting the distribution of incidence and death of COVID-19 worldwide. Despite the multitude of possible reasons proposed to explain COVID-19 dispersion, our current knowledge of this pandemic is still

incomplete. Environmental and genetic factors have been proposed as the disease's plausible risk factors (Abdelzaher et al. 2020; X. Liu et al. 2021). Betacoronaviruses, such as MERS and SARS, are not thought to be seasonal but it is not clear for COVID-19 (Sajadi et al. 2020). In this regard, the role of environmental factors such as weather parameters (temperature, humidity, precipitation, wind speed) is still controversial among researchers. Several studies revealed a significant negative association between temperature (Biktasheva 2020; Li et al. 2020a, b, c, d; Poirier et al. 2020; Prata et al. 2020; Qi et al. 2020; Rendana 2020; Rosario et al. 2020; Rubin et al. 2020; Sehra et al. 2020; Sobral et al. 2020; Y. Wu et al. 2020a, b), humidity (Meo et al. 2020; Monami et al. 2020; Qi et al. 2020; Wu et al. 2020a, b), precipitation (Del Rio and Camacho-Ortiz 2020; Hossain et al. 2020; Menebo 2020), and wind speed (Bolaño-Ortiz et al. 2020; Coccia 2020; Haque and Rahman 2020; Hossain et al. 2020; Rendana 2020; Rosario et al. 2020) and incidence (or death) of COVID-19, but some studies have shown a positive correlation for temperature, humidity, and wind speed (Azuma et al. 2020; Bolaño-Ortiz et al. 2020; Kolluru et al. 2021; Luo et al. 2020; Menebo 2020; Roy 2020; Runkle et al. 2020; Singh et al. 2020; Xie and Zhu 2020). Wu et al. (2020a, b) conducted a multivariate analysis study to investigate the effect of different weather factors such as daily average temperature, relative humidity, and wind speed on new cases and deaths of COVID-19 in China (Wu et al. 2020a, b). Strong correlations were found with the average temperature, humidity, and wind speed and total number of confirmed cases. The study further revealed that a 1 °C increase in temperature can reduce 3.08% (95% CI: 1.53%, 4.63%) and 1.19% (95% CI: 0.44%, 1.95%) of daily new cases and daily new deaths, respectively (Wu et al. 2020a, b). Other studies have suggested that the long-term effects of different weather parameters need to be investigated in more detail (Runkle et al. 2020; Sehra et al. 2020).

Some studies use the number of confirmed cases in relation to environmental factors, which would not be a good criterion for comparison between different regions, due to differences in testing capacity. The proportion of cases and deaths per capita population may be a better measure for comparison between regions. Also, if the areas to be considered are smaller scale or micro-regions, the results will be more accurate, because on a small scale, the climate and COVID-19 variables can be more precise for a specific geographic context, and as a result, the relationship between them is more indicative of genuine local conditions than averaged values over a large geospatial area would be (Sobral et al. 2020). Also, there is a limited study to investigate long-term effects of meteorological parameters such as temperature, wind speed, and humidity on COVID-19 distribution. Another limitation of country-level ecological studies is that they exclude variations in meteorological attributes at a regional level (Wu et al. 2020a, b); this generalization to the whole country can result in bias.

The United Kingdom (UK) is one of the leading European countries in the free dissemination of COVID-19 data. The UK is seventh worldwide in the number of cases (1,557,011 persons) and fifth in the number of deaths (56,533 persons) as of 26 November 2020 (GOV.UK 2021). In this study, we use multivariate regression analyses and control for the effect of population density (number of people per area of land) and median age variables, to explore the effects of weather parameters such as temperate, relative humidity, wind speed, precipitation, and dew point on the incidence of COVID-19 case and death rate at 406 UK authorities before mass vaccination. Our results provide useful implications for researchers, medical centers, policymakers, and the public.

Material and methods

Study area

The current ecological study includes 406 local authorities that cover the majority of the UK (60.85° to 49.95° latitude and 1.76° to −8.18° longitude) with approximately 248,532 square kilometers (km²). Figure 1 illustrates the locations of the UK areas. The UK consists of four devolved nations, including England, Scotland, Wales, and Northern Ireland. In general, the climate of the UK is a temperate oceanic climate (or Cfb on the Köppen climate classification)—cool and often cloudy and rainy (Peel et al. 2007).

The mean temperature, rainfall, wind speed, and relative humidity for the UK from 1981 to 2010 are illustrated in Fig. 2, based on data from the UK Government Met Office (https://www.metoffice.gov.uk/) (Met Office 2021). Maximum and minimum temperature and rainfall reported 12.40 (°C), 5.30 (°C), and 1154 (mm) for the UK, respectively. The UK's population in 2020 was 67,886,011 (83. 2% urban), with a median age of 40.5 years in 2020 (www. worldometers.info).

Meteorological and weather data

We collected the secondary data on the weather and climate parameters that were provided by several public-available websites (freemeteo.co.uk 2020; timeanddate 2020; Weather Atlas 2020). The websites report data on temperature (high, low, mean) (°C), precipitation (mm), relative humidity (%), dew point (°C), wind speed (km/h), pressure (mbar), and visibility (km) during 1985–2015. Before the statistical analysis, we conducted several data quality controls to confirm the validity of meteorological data. First, if there were data non-normally distributed in the records, they were removed from the analysis. Second, if the missing rate of data for the amount of annual data in the stations was more than 5%, we decided that we would

Fig. 1 Study location in the UK (https://www.gov.uk/); UTLA is 7-day rolling rate of new cases
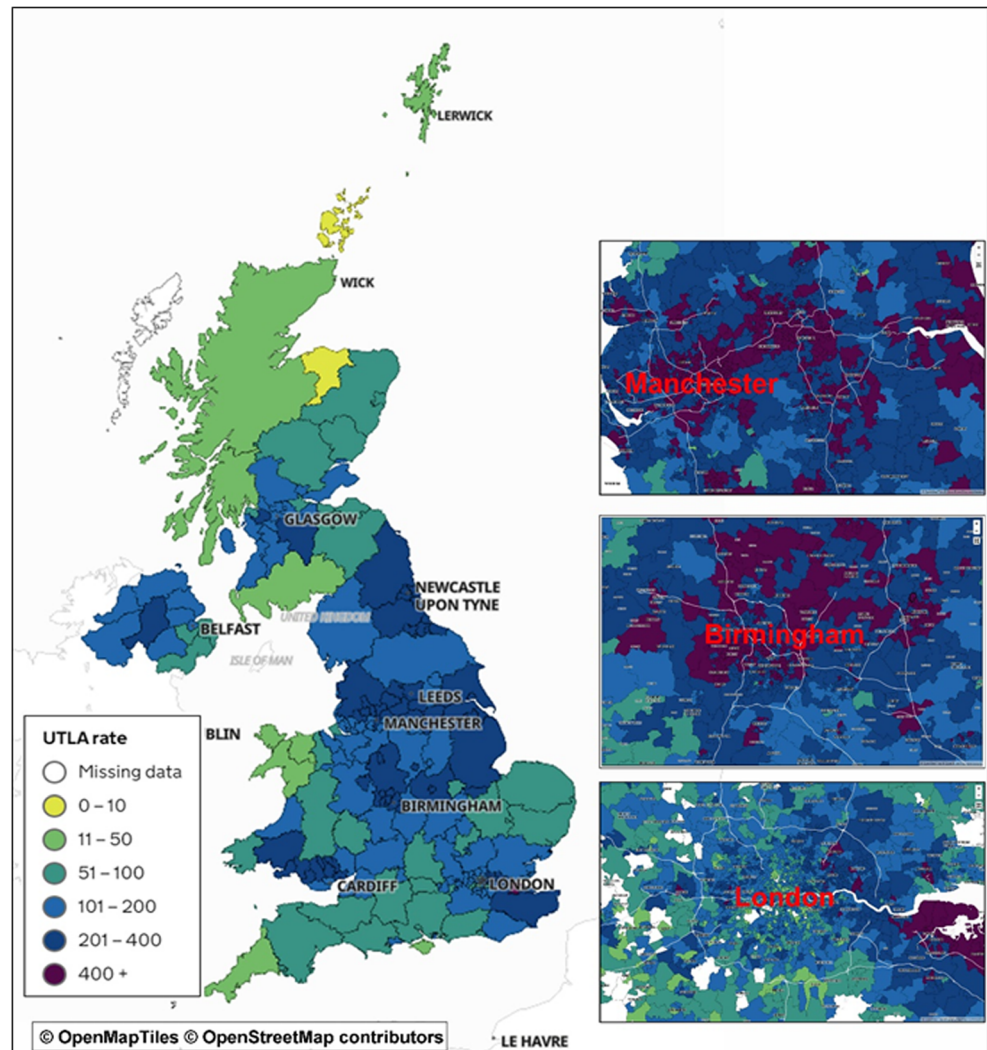
delete that station. Nevertheless, none of the stations needed to be deleted. Finally, the final data were checked with the values of meteorological parameters at nearby stations.

COVID-19 and confounder variable data

This study was carried out based on publicity available secondary data on COVID-19, which the UK Government has collected and published on its websites. Total positive confirmed cases, total deaths within 28 days of positive test, and case and death rates per 100,000 population were collected from the "official UK Government website for data and insights on COVID-19" (https://coronavirus.data.gov.uk) as of November 13, 2020. The reported COVID-19 data are regularly updated on standard website on daily basis. Two main variables, population density (person per square area) and median age, were included in the study as potential confounding covariates (https://www.ons.gov.uk/ and https://lginform. local.gov.uk/).

Statistical analysis

Descriptive analyses were performed for all obtained data. Spearman and Pearson correlation test was applied to analyze the association between COVID-19 variables (number and rate) and demographic and meteorological parameters. Also to determine a net effect of the independent variables, multivariable regression analysis was used to explore the associations between COVID-19 case and death rates per 100,000 and meteorological factors by adjusted to population density and median age. COVID-19 data and meteorological or demographic variables were normalized before we entered them into the model, if they displayed non-normal distribution. We fixed the distributions of all studied variables with a logarithmic transformation. For comparison of mean quantitative variables, the Student T test or Mann–Whitney U test was performed. Statistical analyses were carried out using IBM SPSS Statistics 20 software and the graphical representations were performed using GraphPad Prism (version 6). All tests were
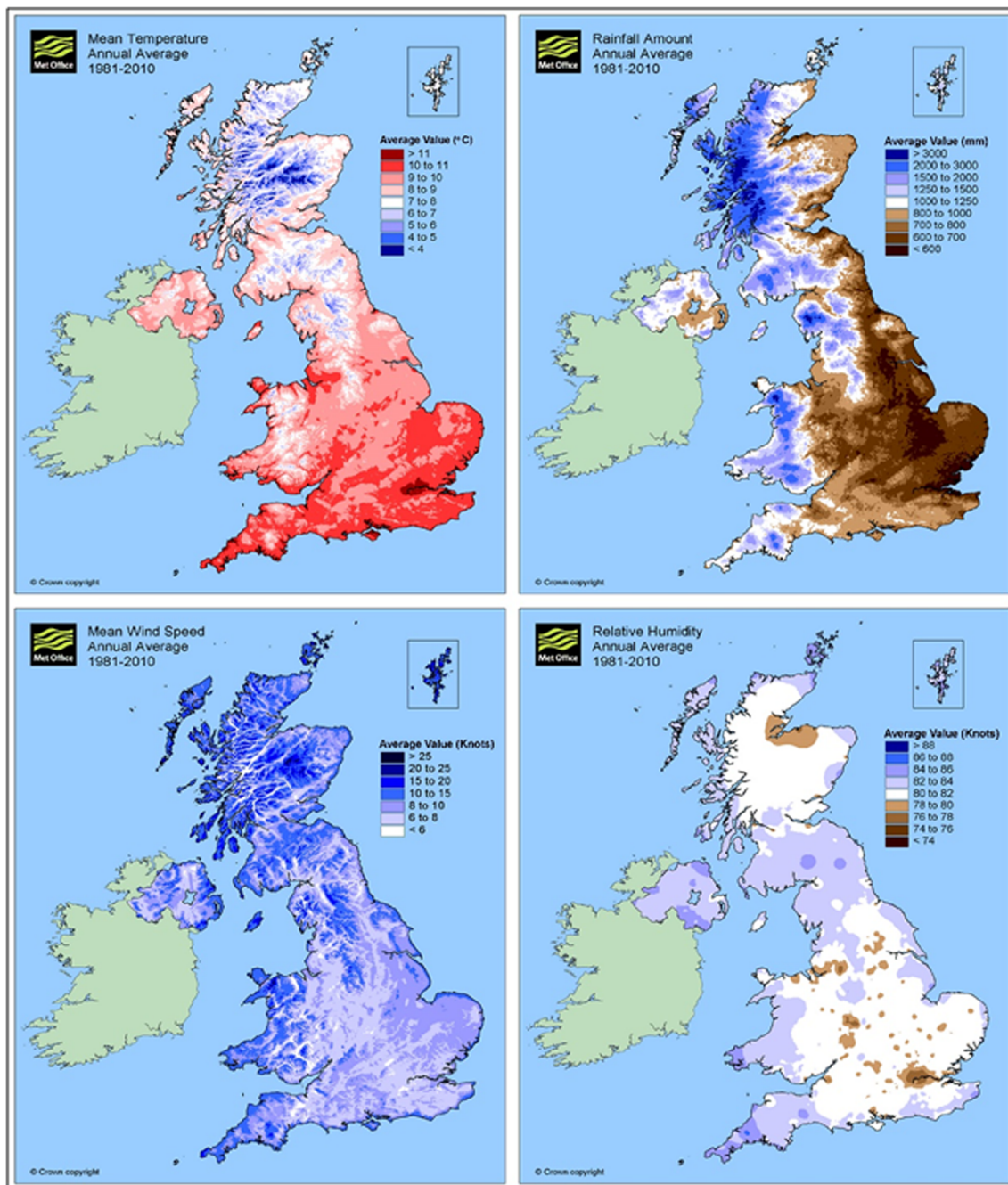
Fig. 2 Contour plots created from UK Met Office monitors showing average of meteorological parameters (Met Office 2021)

two-sided, and a value P < 0.05 was considered statistically significant.

Results

Description analysis

A total of 1,379,388 cumulative positive confirmed cases and 52,502 deaths had been reported for UK as of November 13,

2020. Lancashire, Birmingham, Leeds, and Manchester were the four regions with the most cases of COVID-19 (absolute number); also, Essex, Lancashire, Kent, and Birmingham had the most deaths of COVID-19. Blackburn with Darwen, Oldham, Manchester, and Rochdale had the highest case rate per 100,000 population, and Tameside, Wigan, Rochdale, and Wyre had the highest death rate per 100,000 population in the UK regions.

The geographic distribution (Fig. 3) for the 7-day rolling rate of new cases of COVID-19 by specimen date across

various areas was visualized on a weekly basis from March 21 to November 13, 2020. Over the past few months (May to Aug.), the incidence of the disease has decreased but has risen again (after September to now).

The descriptive statistics for long-term meteorological parameters, COVID-19 variables (as of November 13, 2020), population density, and median age are demonstrated in Table 1.

Correlation analysis

Table 2 shows the results of correlation analysis between independent (meteorological parameters), dependent (COVID-19 variables), and demographic (population density and median age) variables for the UK authorities. The analysis revealed a significant negative correlation between average high temperature (r = −.33 for incidence and r = −.19 for death), mean temperature(r = −.22 for incidence and r = −.13 for death), dew point (r = −.29 for incidence and r = −.29 for death), and COVID-19 incidence and death rates,

respectively. Interestingly, the median age (also age >65 and >85) was inversely correlated to the COVID-19 variables, and the regions with high age 0–15 had a significantly higher death and incidence of COVID-19 rate (P <.001). On the other hand, Pearson and Spearman correlation analyses were used to explore the precise associations between COVID-19 variables and meteorological parameters in various subgroups (Table 3). The results show that, in areas with a higher temperature (>10 °C), precipitation was associated with increased incidence (r=.31) of COVID-19. By sharp contrast, in colder areas (≤10 °C), it was linked with decreased rates of disease (incidence (r=−.18) and mortality (r=−.16) of COVID-19 (P <.05)).

Wind speed was significantly associated with increased (P <.05) incidence of COVID-19 in areas with high case rate (higher 1500 per 100,000 population), high death rate (higher 100 per 100,000 population), high humidity (>75%), low precipitation (≤48 mm per month), low mean temperature (≤10 °C), and low visibility (≤15 km).
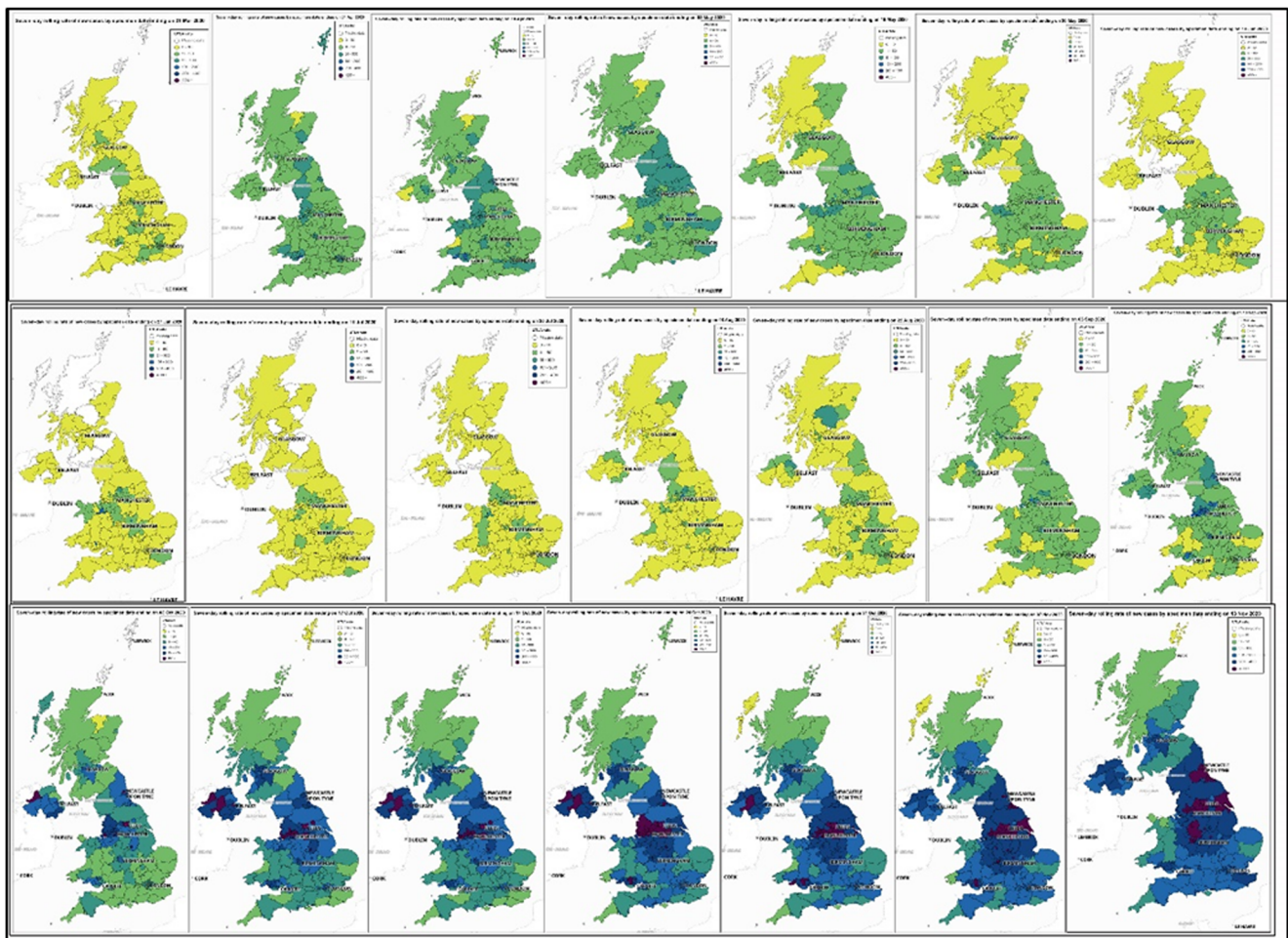

Fig. 3 Weekly distribution of COVID-19 7-day new cases rate up to 13 December 2020 for UK, each figure corresponds to a week, the colors are white = missing data, yellow =0–10 new case rate, light green = 11–50 new case rate, dark green = 51–100 new case rate, light blue = 101–200 new case rate, dark blue = 201–400 new case rate, lollipop = >400 new case rate

Table 1 Descriptive statistic of study

Cases	Mean	SD	Median	IQR$_{25\%,\ 75\%}$		Min	Max
Cases per 100,000 population	1803.78	1037.81	1494.00	1079.63	2276.25	157.20	5800.40
Deaths per 100,000 population	75.67	31.56	72.10	52.75	95.65	3.70	195.60
Average high temperate (°C)	21.03	2.00	21.00	20.00	22.00	10.00	34.00
Average low temperate (°C)	2.05	1.16	2.00	1.00	3.00	−4.00	6.00
Average mean temperate (°C)	10.10	1.09	10.00	10.00	11.00	3.00	19.00
Average precipitation (mm)	43.04	20.57	39.25	30.40	49.70	2.60	190.00
Average relative humidity (%)	79.13	3.58	80.00	78.00	81.00	65.00	89.00
Average dew point (°C)	6.79	0.74	7.00	6.00	7.00	2.00	11.00
Average wind speed (km/h)	15.68	2.76	15.00	14.00	17.00	11.00	27.00
Average pressure (kPa)	101.47	0.19	101.52	101.43	101.57	100.03	101.82
Average visibility (km)	12.86	3.61	11.00	10.00	15.00	9.00	28.00
Population density (pop./km^2)	1512.76	2434.44	526.00	187.00	1929.00	8.80	16237.00
Median age (year)	42.46	4.97	42.70	38.90	46.30	28.90	54.30

Additional analyses were done for area categories (high and low variables) to explore the effect of independent variables on COVID-19 incidence and death rates (Fig. 4).

There were significant differences between COVID-19 incidence in high and low mean temperature, wind speed, dew point, pressure, and humidity (p <0.05) (Fig. 4). Among lower mean temperature and lower dew point areas, the average incidence rates were 2056.86 (CI: 1909.49–2204.23) and 2281.28 (CI: 2069.05–2493.51), and death rates were 81.55 (CI: 77.40–85.70) and 88.44 (CI: 82.32–94.55) respectively

Table 2 Bivariate correlation coefficient matrix for COVID-19 variables, meteorological parameters, and demographic variables for 406 areas of the UK

1. Cases	1	2	3	4	5	6	7	8.	9	10	11	12
2. PC	.702**	1.000										
3. Death	.899**	.516**	1.000									
4. PD	.470**	.713**	.598**	1.000								
5. AHT	−.147**	−.327**	−0.048	−.188**	1.000							
6. ALT	0.000	−0.056	0.008	−0.038	.170**	1.000						
7. AMT	−0.078	−.219**	−0.027	−.130*	.577**	.785**	1.000					
8. APrec.	−0.080	−0.094	−0.068	−0.086	−0.008	.185**	.105*	1.000				
9. ARH	−0.037	0.007	−0.069	−0.078	−.622**	−.500**	−.616**	.124*	1.000			
10. ADP	−.171**	−.292**	−.160**	−.293**	.373**	.473**	.611**	.237**	−0.063	1.000		
11. AWS	0.082	.192**	0.046	.149**	−.498**	0.098	−.128*	−0.062	.313**	−0.026	1.000	
12. AP	−0.105	−0.073	−0.046	0.041	.364**	.111*	.203**	.219**	−.265**	−0.002	0.022	1.000
13. Visibility	−.153**	−0.092	−.140**	−0.055	−.113*	−.556**	−.463**	.234**	.351**	−.189**	−.140**	−0.032
14. Median age	−.586**	−.303**	−.507**	−.100	−.159**	−.136**	−.143**	.037	.251**	.011	.104*	.231**
15. Pop. density	.429**	.361**	.393**	.287**	.261**	.184**	.246**	−.118*	−.336**	.020	−.138**	−.052
16. Age=0-15	.319**	.229**	.357**	.257**	.365**	.097	.204**	−.059	−.328**	−.009	−.103	.106
17. Age >p65	−.520**	−.339**	−.434**	−.123*	−.253**	−.129*	−.160**	.030	.330**	.099	.125*	.187**
18. Age >85	−.539**	−.429**	−.424**	−.186**	−.073	−.049	−.014	.012	.192**	.186**	.013	.261**

** P < 0.01, * P < 0.05, *PC* proportion of case per million, *PD* proportion of death per million, *AHT* average high temperature, *ALT* average low temperature, *AMT* average mean temperature, *APrec.* average precipitation, *ARH* average relative humidity, *ADP* average dew point, *AWS* average wind speed, *AP* average pressure, *PDencity* population density (person per square kilometer)

Table 3 Correlation of COVID-19 incidence and death (cumulative number and rate per 100,000) and meteorological parameters for 406 areas of the UK; categories for all variables (>: high and ≤: low)

Variables	Cases	PC	Death	PD	Cases	PC	death	PD
PC >1500 per 100,000					**PC ≤1500 per 100,000**			
Average high temperate (°C)	−0.078	−.323**	−0.060	−.244**	.244**	.305**	.287**	.354**
Average low temperate (°C)	0.048	0.021	0.072	0.101	0.068	0.110	0.067	0.056
Average mean temperate (°C)	0.005	−0.121	0.047	0.042	0.114	0.126	0.125	0.100
Average precipitation (mm)	−0.063	−0.120	0.002	−0.003	−0.072	0.075	−0.074	−0.025
Average relative humidity (%)	−0.013	0.097	−0.025	−0.031	−.188*	−.338**	−.193*	−.314**
Average dew point (°C)	−0.114	−.151*	−0.106	−.153*	−0.003	−.166*	0.003	−.150*
Average wind speed (km/h)	−0.006	.159*	−0.011	0.131	−0.090	−0.118	−0.094	−0.102
Average pressure (kPa)	−.390**	−.359**	−.283**	−0.139	−0.020	−.179*	−0.006	−0.080
Average visibility (km)	−0.113	−0.048	−0.082	0.071	−0.139	−0.046	−.169*	−.154*
PD >100 per 100,000					**PD ≤100 per 100,000**			
Average high temperate (°C)	−0.142	−.313**	0.039	−0.133	−0.048	−.192**	0.071	−0.020
Average low temperate (°C)	0.090	0.143	0.087	−0.002	−0.042	−.139*	−0.006	−0.074
Average mean temperate (°C)	−0.023	−0.076	0.080	−0.015	−0.072	−.235**	−0.013	−.135*
Average precipitation (mm)	−0.096	−0.093	−0.054	−0.088	−0.061	−0.071	−0.072	−0.090
Average relative humidity (%)	0.032	0.097	−0.072	0.054	−0.053	−0.058	−0.080	−0.114
Average dew point (°C)	−0.105	−0.111	−0.009	−0.086	−.164**	−.344**	−0.114	−.247**
Average wind speed (km/h)	0.117	.265*	−0.009	0.106	0.008	0.092	−0.013	0.081
Average pressure (kPa)	−.459**	−.488**	−.270*	−0.238	−.267**	−.419**	−.139*	−.227**
Average visibility (km)	−0.097	−0.094	−0.091	−0.033	−.167**	−0.080	−.194**	−.139*
Population density >300 per km²					**Population density ≤300 per km²**			
Average high temperate (°C)	−.273**	−.508**	−.132*	−.308**	−.085	−.181*	.023	−.070
Average low temperate (°C)	−.088	−.186**	−.056	−.134*	−.035	−.040	−.081	−.098
Average mean temperate (°C)	−.165**	−.369**	−.078	−.214**	−.140	−.202*	−.131	−.215*
Average precipitation (mm)	−.011	−.062	.008	−.036	−.116	−.112	−.196*	−.205*
Average relative humidity (%)	.130*	.263**	.038	.097	−.071	−.206*	−.039	−.174
Average dew point (°C)	−.227**	−.346**	−.175**	−.281**	−.094	−.256**	−.144	−.332**
Average wind speed (km/h)	.193**	.337**	.136*	.260**	−.034	.021	−.076	.030
Average pressure (kPa)	−.413**	−.473**	−.259**	−.245**	−.133	−.349**	−.078	−.294**
Average visibility (km)	−.048	.065	−.047	.113	−.088	−.087	−.096	−.109
Median age > 45 years					**Median age ≤ 45 years**			
Average high temperate (°C)	−.067	−.105	.022	−.052	−.311**	−.446**	−.174**	−.251**
Average low temperate (°C)	−.197*	−.158	−.177	−.115	.001	−.063	.029	−.022
Average mean temperate (°C)	−.269**	−.274**	−.189	−.173	−.107	−.223**	−.038	−.111
Average precipitation (mm)	−.082	−.133	−.146	−.162	−.047	−.103	−.008	−.068
Average relative humidity (%)	−.080	−.248*	−.078	−.230*	.146*	.206**	.058	.040
Average dew point (°C)	−.229*	−.394**	−.202*	−.361**	−.169**	−.226**	−.159*	−.227**
Average wind speed (km/h)	.034	.043	−.030	−.004	.176**	.260**	.140*	.213**
Average pressure (kPa)	−.250*	−.429**	−.166	−.320**	−.303**	−.341**	−.184*	−.184*
Average visibility (km)	−.081	−.098	−.084	−.075	−.073	−.042	−.071	−.015
Percentage of children > 20%					**Percentage of children ≤ 20**			
Average high temperate (°C)	−.352**	−.494**	−.169	−.352**	−.196**	−.258**	−.139*	−.178**
Average low temperate (°C)	−.026	−.100	.017	−.025	−.063	−.064	−.086	−.090
Average mean temperate (°C)	−.159	−.286**	−.002	−.090	−.167**	−.208**	−.163*	−.188**
Average precipitation (mm)	−.175	−.244*	−.100	−.171	−.062	−.076	−.075	−.084
Average relative humidity (%)	.159	.271**	.058	.175	.026	−.047	.032	−.086
Average dew point (°C)	−.310**	−.393**	−.225*	−.243*	−.169**	−.259**	−.206**	−.312**
Average wind speed (km/h)	.265*	.418**	.144	.331**	.071	.109	.042	.078

Table 3 (continued)

Variables	Cases	PC	Death	PD	Cases	PC	death	PD
Average pressure (kPa)	−.335**	−.418**	−.263*	−.433**	−.359**	−.377**	−.248**	−.190**
Average visibility (km)	−.028	.045	−.037	.050	−.136*	−.128*	−.113	−.063
	Mean temperature >10 °C				**Mean temperature ≤10 °C**			
Average high temperate (°C)	0.069	0.033	.214*	.251**	−.144*	−.272**	−0.110	−.257**
Average low temperate (°C)	−0.019	0.083	−0.057	−0.012	.215**	.298**	.171*	.236**
Average mean temperate (°C)	0.157	−0.012	.183*	0.059	0.114	.138*	0.094	0.127
Average precipitation (mm)	.194*	.313**	0.157	0.148	−.161*	−.181**	−.154*	−.155*
Average relative humidity (%)	−0.059	−0.073	−.177*	−.275**	−.127*	−.244**	−0.029	−.190**
Average dew point (°C)	−.319**	−.328**	−.370**	−.369**	−0.046	−0.126	−0.058	−.187**
Average wind speed (km/h)	0.099	0.115	0.068	0.025	0.015	.137*	−0.022	0.104
Average pressure (kPa)	−0.166	−.192*	−0.101	−0.100	−.364**	−.387**	−.304**	−.306**
Average visibility (km)	−0.118	−0.108	−0.055	0.026	−.249**	−.270**	−.226**	−.207**
	Mean precipitation >48 mm				**Mean precipitation ≤48 mm**			
Average high temperate (°C)	0.013	−.216**	0.094	−0.090	−.273**	−.441**	−.156*	−.279**
Average low temperate (°C)	−0.030	−.236**	0.033	−0.130	0.047	0.110	−0.017	0.045
Average mean temperate (°C)	0.079	−.195*	0.129	−0.117	−.157*	−.210**	−0.131	−0.130
Average precipitation (mm)	0.017	0.146	−0.043	0.034	−0.073	−0.094	−0.111	−.167*
Average relative humidity (%)	−0.019	0.134	−0.078	0.015	−0.066	−.134*	−0.037	−.173*
Average dew point (°C)	−0.012	−0.158	−0.044	−.239**	−.263**	−.363**	−.237**	−.335**
Average wind speed (km/h)	0.096	0.087	0.095	0.080	0.059	.228**	0.017	.178**
Average pressure (kPa)	−0.136	−.346**	−0.100	−.305**	−.453**	−.484**	−.298**	−.262**
Average visibility (km)	−.194*	−0.025	−.193*	0.000	−0.115	−0.105	−0.096	−0.075
	Mean relative humidity >75%				**Mean relative humidity ≤75%**			
Average high temperate (°C)	−.153**	−.288**	−0.096	−.221**	0.187	.255*	0.208	0.172
Average low temperate (°C)	0.079	0.084	0.041	0.031	−.241*	−0.212	−.247*	−0.179
Average mean temperate (°C)	−0.045	−0.110	−0.047	−0.099	0.225	−0.033	0.220	0.009
Average precipitation (mm)	−0.077	−0.062	−0.102	−0.098	.308**	.292*	.293*	0.175
Average relative humidity (%)	−.153**	−.202**	−0.115	−.197**	.271*	0.162	0.181	0.013
Average dew point (°C)	−.172**	−.272**	−.184**	−.310**	−0.097	−0.073	0.037	0.201
Average wind speed (km/h)	0.041	.124*	0.029	.120*	0.223	0.124	0.208	0.128
Average pressure (kPa)	−.416**	−.444**	−.327**	−.309**	0.103	0.028	0.022	−.261*
Average visibility (km)	−.205**	−.165**	−.174**	−0.088	0.178	.256*	0.208	0.179
	Mean dew point >6 °C				**Mean dew point ≤6 °C**			
Average high temperate (°C)	−0.115	−.310**	0.077	−0.007	0.081	.191*	−0.035	0.042
Average low temperate (°C)	0.009	0.033	−0.005	0.018	.250**	.353**	.241**	.336**
Average mean temperate (°C)	−0.061	−.221**	0.018	−0.082	.257**	.455**	.209*	.403**
Average precipitation (mm)	0.083	.153*	0.047	0.062	−.220*	−.363**	−0.149	−.235*
Average relative humidity (%)	−0.077	−0.019	−.165*	−.208**	−0.058	−.206*	0.045	−0.093
Average dew point (°C)	−.228**	−.201**	−.273**	−.308**	.309**	.370**	.315**	.360**
Average wind speed (km/h)	.129*	.236**	0.083	.176**	−0.157	−0.172	−.184*	−.219*
Average pressure (kPa)	−.353**	−.462**	−.177*	−.295**	−.262**	−0.078	−.293**	0.038
Average visibility (km)	−.130*	−0.030	−.134*	−0.025	−.258**	−.373**	−.220*	−.233*
	Mean wind speed >15 km/h				**Mean wind speed ≤15 km/h**			
Average high temperate (°C)	−0.036	−0.128	0.045	−0.059	−.164*	−.372**	−0.090	−.239**
Average low temperate (°C)	0.105	0.139	0.070	0.118	−0.080	−.239**	−0.023	−0.119
Average mean temperate (°C)	0.098	0.064	0.118	0.110	−.164*	−.384**	−0.109	−.249**
Average precipitation (mm)	−0.056	−0.152	−0.004	−0.064	−0.062	0.010	−0.082	−0.029
Average relative humidity (%)	−.202*	−.295**	−0.163	−.326**	0.049	.148*	−0.021	0.025
Average dew point (°C)	−0.097	−0.138	−0.042	−0.085	−.241**	−.455**	−.247**	−.445**

Table 3 (continued)

Variables	Cases	PC	Death	PD	Cases	PC	death	PD
Average wind speed (km/h)	−0.049	0.062	−0.062	0.119	.191**	.211**	.193**	.257**
Average pressure (kPa)	−.400**	−.378**	−.265**	−.218*	−.269**	−.425**	−.181*	−.325**
Average visibility (km)	−.337**	−.310**	−.263**	−0.119	0.034	.199**	−0.049	0.037
	Mean pressure >101.40 KPa				**Mean pressure ≤101.40 kPa**			
Average high temperate (°C)	−0.061	−.273**	0.121	−0.115	−0.008	−0.079	−0.075	−0.105
Average low temperate (°C)	0.002	−0.062	0.033	−0.020	0.115	0.096	0.025	0.007
Average mean temperate (°C)	−0.094	−.242**	0.015	−0.107	0.112	0.050	−0.003	−0.049
Average precipitation (mm)	−0.018	−0.085	−0.003	−0.084	−0.197	−0.222	−0.198	−0.112
Average relative humidity (%)	−0.077	−0.038	−.143*	−.138*	−0.117	−0.109	−0.012	−0.016
Average dew point (°C)	−.160*	−.326**	−0.118	−.323**	0.118	0.027	0.028	−0.086
Average wind speed (km/h)	0.061	.203**	−0.011	.148*	−0.071	−0.005	−0.003	0.095
Average pressure (kPa)	−.204**	−.444**	−0.095	−.381**	−.565**	−.668**	−.519**	−.506**
Average visibility (km)	−0.112	−0.079	−0.101	−0.068	−.293*	−0.220	−.284*	−0.182
	Mean visibility >15 km				**Mean visibility ≤15 km**			
Average high temperate (°C)	−0.074	−0.096	−0.103	−0.143	−.184**	−.493**	−0.023	−.232**
Average low temperate (°C)	0.065	0.009	0.122	0.089	−.175**	−.228**	−.185**	−.230**
Average mean temperate (°C)	0.036	−0.001	0.078	0.040	−.220**	−.511**	−.153*	−.370**
Average precipitation (mm)	−0.123	−0.118	−0.089	−0.052	−0.035	−.133*	−0.004	−0.108
Average relative humidity (%)	−0.123	−.181*	−0.051	−0.073	0.084	.207**	−0.005	0.004
Average dew point (°C)	−0.125	−.217**	−0.084	−.172*	−.243**	−.396**	−.250**	−.437**
Average wind speed (km/h)	−0.117	−.161*	−0.027	−0.014	.188**	.419**	0.069	.225**
Average pressure (kPa)	−.285**	−.382**	−.186*	−.210*	−.387**	−.490**	−.239**	−.365**
Average visibility (km)	−.206**	−0.133	−.192*	−0.096	−0.128	−0.075	−0.111	0.006

**P < 0.01, * P < 0.05, *PC* proportion of case per million, *PD* proportion of death per million

(Fig. 4). Also, COVID-19 incidence in higher mean temperature and dew point areas were 1446.76 (CI: 1296.71–1596.81) and 1605.98 (CI: 1484.40–1727.56 (Fig. 4). However, the regions with low mean temperature (≤10 °C), low pressure (≤101.40 kPa), and low dew point (≤6 °C) showed significantly higher COVID-19 incidence when compared to high-value regions (Fig. 4).

Regression analysis

Table 4 presents the results of regression analyses of COVID-19 incidence and death rates and meteorological parameters. Results revealed a negative association of high and mean temperature, dew point, and pressure (adjusted for population density and median age) on COVID-19 incidence rate (P <0.001). On the other hand, there were positive significant associations for humidity and wind speed and COVID-19 incidence rate.

In multiple regression analysis, the results showed that relative humidity, wind speed, and population density have positive associations with COVID-19 incidence rate (P <0.05, Table 5). In the case of COVID-19 death rate (adjusted for population density and median age), significant associations

were found for high temperature, mean temperature, dew point, wind speed, and pressure (p <0.01).

Discussion

The novel coronavirus pandemic has become a major challenge globally, with approximately 2.5 million deaths and as of yet no clear exit from the pandemic (WHO 2021). The pattern of COVID-19 distribution is related to extra-human conditions, such as weather and demographic structural conditions (Cohen 2020). Several factors could affect the incidence and death distribution of COVID-19 in various regions. However, moving toward the micro-regional (or local authority level) studies can further clarify the effects of environmental factors such as meteorological parameters (Sobral et al. 2020). In this analysis of 406 UK local authorities, change in temperature (mean, high and low), wind speed, humidity, precipitation, dew point, pressure, visibility, population density, and median age were associated with the cumulative number and rate of incidence and death of COVID-19. The primary correlation results of this study (Table 2) indicate that, of these several meteorological factors, long-term high temperature and dew point have been the most
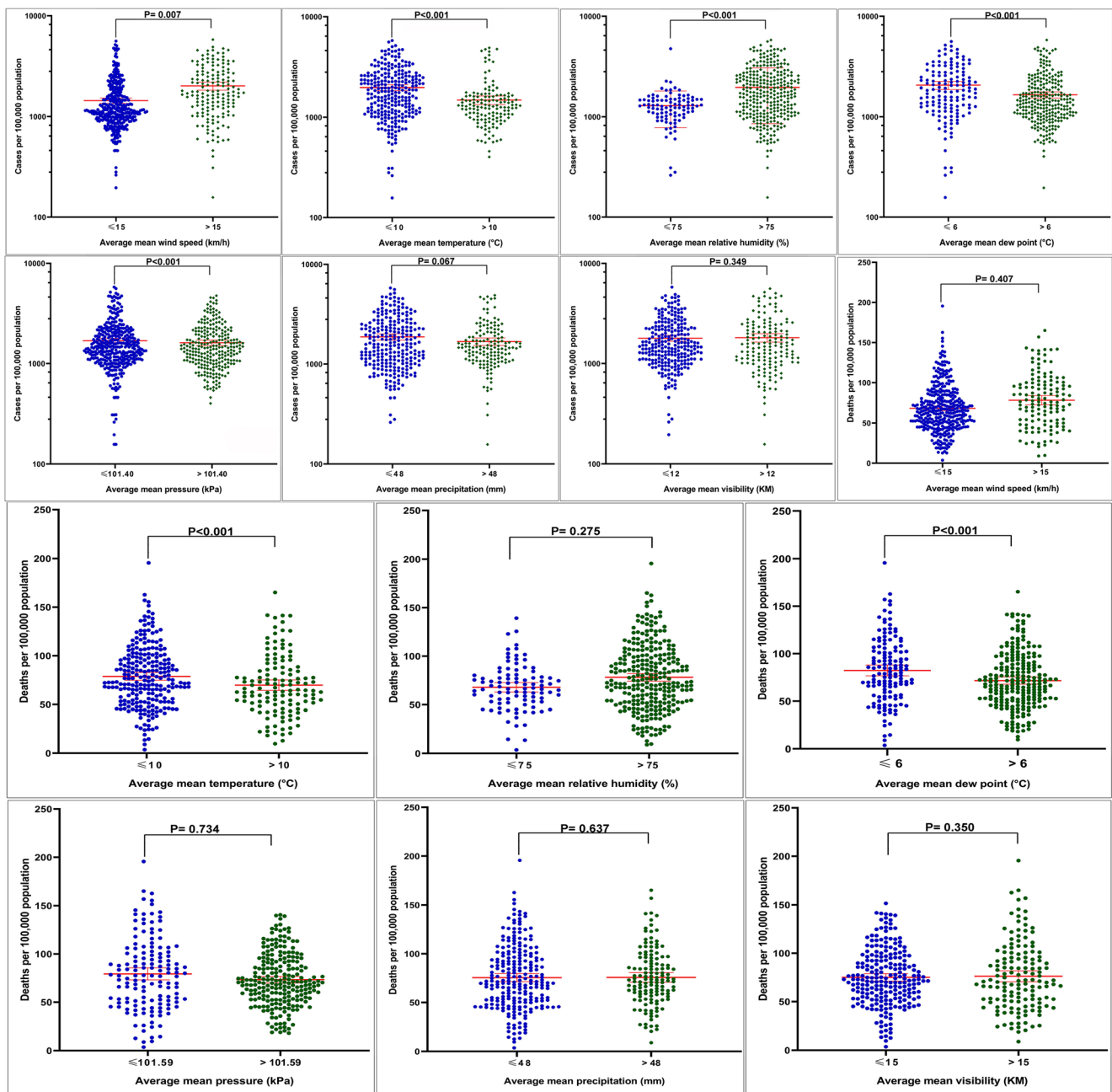
Fig. 4 Differences of COVID-19 variables in low and high subgroups by two independent samples test. Red horizontal lines represent group means with 95% CI. P is *P*-value

significant in reducing COVID-19 incidence and death rates, but wind speed significantly increased those rates. It should be noted that the effect of environmental parameters on disease incidence can be more reliable than death, because before the dire situation, their people live in natural environments and everyone's conditions are the same, but for mortality, other parameters such as the number of hospital beds, ICU bed, and the health care system of regions can play a more effective role. There are several studies indicating that regions with higher temperatures have lower rates of the disease (Biktasheva 2020; Li et al. 2020a, b, c, d; Poirier et al. 2020; Prata et al. 2020; Qi et al. 2020; Rendana 2020;

Rosario et al. 2020; Rubin et al. 2020; Sehra et al. 2020; Sobral et al. 2020; Y. Wu et al. 2020). Our study also revealed a significant association of the COVID-19 incidence and death rate with average high temperature and mean temperature in the multivariable analysis, after adjusting for confounding variables.

Temperature and COVID-19

There are some factors like latitude and socio-demographic factors (Bao et al. 2016) and air pollution (Cai et al. 2007) that influence the association between temperature and mortality.

Table 4 Regression coefficients for mutually adjusted associations between COVID-19 incidence and death per capita rates and meteorological parameters (adjusted with population density and median age)

Covariates	Unstandardized coefficients		Standardized coefficients	t	Sig.	VIF	R^2
	B	Std. error	Beta				
Log cases per million							
Log average high temperate	−1.382	.280	−.247	−4.933	**.000**	1.109	.236
Log average low temperate	−.085	.062	−.072	−1.377	.169	1.047	.188
Log average mean temperate	−.677	.240	−.145	−2.823	**.005**	1.125	.200
Log average precipitation	−.079	.058	−.067	−1.349	.178	1.021	.180
Log average relative humidity	2.658	.624	.220	4.262	**.000**	1.147	.218
Log average dew point	−.918	.222	−.204	−4.137	**.000**	1.061	.221
Log average wind speed	.518	.164	.157	3.167	**.002**	1.044	.205
Log average pressure	−80.487	16.775	−.254	−4.798	**.000**	1.105	.250
Log average visibility	−.036	.118	−.016	−.304	.761	1.121	.183
Deaths per million							
Log average high temperate	−132.660	39.743	−.182	−3.338	**.001**	1.093	.135
Log average low temperate	−13.267	9.177	−.083	−1.446	.149	1.057	.105
Log average mean temperate	−82.902	33.807	−.138	−2.452	**.015**	1.136	.121
Log average precipitation	−10.774	8.517	−.067	−1.265	.207	1.006	.107
Log average relative humidity	92.310	90.375	.058	1.021	.308	1.131	.105
Log average dew point	−165.964	31.885	−.276	−5.205	**.000**	1.081	.175
Log average wind speed	78.067	24.272	.171	3.216	**.001**	1.037	.133
Log average pressure	−9487.608	2227.484	−.247	−4.259	**.000**	1.100	.154
Log average visibility	11.802	16.832	.039	.701	.484	1.105	.106

Bold numbers are statistically significant, *VIF* variance inflation factor

In fact, people who live far from or near the equator have a relatively strong adaptive capacity to cold and heat, respectively (Sobral et al. 2020). On the other hand, low temperature may increase the transmissibility of viruses, either by "conserving virulence or weakening the host by cooling the body or drying the respiratory tract" (Jaakkola et al. 2014). Temperature is a multifaceted variable with differential effects on the spread of the virus under different conditions. For example in a study published in JAMA, it was reported that at temperatures below 11 °C, the incidence and mortality rate decreases with increasing average temperature, but the relationship reverses above 11°C, which is in line with our results (Rubin et al. 2020). This finding can be related to more human activities or behaviors in the warm region like the use of parks, total attendance in the park, exercising, playing, and getting fresh air (Eliasson et al. 2007; Thorsson et al. 2007). Also, de Montigny et al. (2012) conducted a study (2007–2008) and found that a 14% and 23% increase in pedestrians was linked

with a 5 °C increase in outdoor ambient temperature and a shift from snowy to dry condition, respectively. The SARS-CoV-2 is primarily and secondary transmitted among people through respiratory droplets, contact routes, and close contact with patients during travels (Adedokun 2020; Burke 2020; Chan et al. 2020; Li et al. 2020a, b, c, d; Liu et al. 2020; Magurano et al. 2020). The findings of a study stated that increased person-to-person contact can increase transmission of the virus on warm and/or sunny days (Azuma et al. 2020). Although with increasing temperature, the transmissibility of COVID-19 disease may decrease due to the reduced survival time of the virus on the surfaces (Magurano et al. 2020; Riddell et al. 2020); however, these findings should be interpreted cautiously, because in the absence of mitigation programs such as travel and outdoor activities restrictions, school closures, isolation, and quarantine of patients, there would be no significant reduction in incidence rates. Therefore, temperature should be considered with the other

Table 5 Regression coefficients for mutually adjusted associations between COVID-19 incidence and death per capita rates and the most important factors (adjusted together)

Covariates	Unstandardized coefficients		Standardized coefficients	t	Sig.	VIF	R^2
	B	Std. error	Beta				
Log cases per million							
Log population density	.153	.030	.426	5.012	**.000**	3.010	0.284
Log average dew point	−1.388	.401	−.280	−3.459	**.001**	2.735	
Log average pressure	−51.405	18.150	−.163	−2.832	**.005**	1.379	
Log average relative humidity	2.009	.965	.181	2.082	**.038**	3.166	
Log average wind speed	.447	.184	.143	2.429	**.016**	1.451	
Log average mean temperate	.870	.505	.171	1.724	.086	4.103	
Log average high temperate	.110	.467	.021	.236	.814	3.187	
Log median age	−.189	.364	−.044	−.518	.605	2.993	
Deaths per million							
Log population density	.193	.028	.631	6.952	**.000**	2.955	0.248
Log median age	1.711	.330	.473	5.180	**.000**	2.990	
Log average dew point	−1.524	.377	−.350	−4.038	**.000**	2.703	
Log average wind speed	.568	.173	.202	3.279	**.001**	1.368	
Log average pressure	−39.528	16.195	−.151	−2.441	**.015**	1.374	
Log average relative humidity	−.982	.862	−.105	−1.140	.255	3.021	
Log average mean temperate	.162	.460	.038	.352	.725	4.176	
Log average high temperate	.692	.421	.154	1.646	.101	3.148	

Bold numbers are statistically significant, *VIF* variance inflation factor

aforementioned environmental factors, including population density, air pollution, wind speed, and humidity. On the other hand, our results revealed a significant positive association of COVID-19 incidence with humidity in the multivariable analysis. Also, it is worthy to mention that the effect sizes are consistently larger for cases per capita compared to deaths per capita. This likely makes sense, because weather has its impact on disease transmission which is one factor out of several ones effecting deaths.

Humidity, dew point, and COVID-19

The multivariable regression associations we discovered, especially within the humidity range, are consistent with the direct relationship of humidity and incidence rate or cumulative number of COVID-19 in other studies (Bolaño-Ortiz et al. 2020; Luo et al. 2020; Singh et al. 2020). Humidity has been introduced as one of the best predictors for the transmission of COVID-19 (Runkle et al. 2020). Several studies found that higher humidity was correlated with increased transmission of viruses such as influenza through fomites, even if viral aerosol transmission reduces in high temperature (Ijaz et al. 1985; Lowen et al. 2007). Runkle et al. (2020) using a lag nonlinear model and case-crossover study showed exposure to humidity was positively associated with transmission of COVID-19 in

US cities (Runkle et al. 2020). In our study, it was also shown that in areas with low wind speeds, higher humidity can increase the incidence of disease (r=.15, P <.05). This may be due to the increased concentration of virus in exposure environment, especially in densest regions, and resulting in the inoculum effect (Rubin et al. 2020), both for COVID-19 and other viruses (Chu et al. 2004; Poulsen et al. 2002; Virlogeux et al. 2015; Watanabe et al. 2010). Correlation and regression analyses showed that the dew point is one of the most important parameters in the COVID-19 distribution (Tables 3, 4, and 5). Higher dew points occur in warmer environments where the persistence of the virus on fomite is shorter (Biryukov et al. 2020; Magurano et al. 2020; Riddell et al. 2020). Category analysis in our study showed at higher dew points (>6 °C), the association between COVID-19 variables and the dew point was negative, but at lower dew points (≤6 °C), it was positive.

Wind speed and COVID-19

Based on our overall results, there is also a positive significant association between wind speed and COVID-19 incidence and death rates, especially in densest regions, which may be related to the inoculum effect. SARS-CoV-2 can spread more in windy conditions because it increases air circulation

(Coşkun et al. 2021; Rosario et al. 2020). However, our study here investigates the interaction between wind speed and COVID-19 variables in the UK regions under different COVID-19 and environmental subgroups (high and low categories). Interestingly, a positive correlation was observed between the incidence of COVID-19 and wind speed in areas with high death rates, high humidity, high population density, high percent of children, low temperature, low visibility, and low precipitation (Table 3). Also, in areas with low wind speed, there is a positive correlation between wind speed and incidence of COVID-19 (P >0.05). In line with these results, Coccia (2020) shows that the regions with little wind and high levels of air pollution have higher cases of COVID-19 (Coccia 2020). The studies also revealed that wind speed has an inverse significant relationship with the rate of COVID-19 (Ahmadi et al. 2020; Rosario et al. 2020) and viral load of SARS (Jiang et al. 2003). On the other hand, among the meteorological variables, wind speed and humidity were the main factors that influenced visibility (these factors more related on particle matter) (Majewski et al. 2014; Zhao et al. 2013). Also, in spring, when there is more rainfall and the humidity is higher, low visibility has been reported (Du et al. 2013). Based on our results, higher humidity correlated with a lower temperature (mean, max, min) (Table 2). Therefore, due to the reasons stated above, wind speed, dew point, and humidity are the most important effective meteorological parameters in the SARS-CoV-2 transmission, as revealed in multivariable regression analysis (Tables 4 and 5). Feng et al. (2020) stated that relative humidity and wind speed may cause SARS-CoV-2 heavily loaded droplets to travel long distances in the air (Feng et al. 2020). Data assessing interactions between humidity, wind speed, and visibility (particulate matter) for SARS-CoV-2 are essential to confirm this claim at the local authority level. Gong et al. (2015) assert that severe fever with thrombocytopenia syndrome virus could be transmitted by aerosol transmission as a possible transmission route (Gong et al. 2015), which must also be considered in the case of COVID-19.

Precipitation and COVID-19

Higher total numbers and per capita rates of COVID-19 cases and deaths are not correlated with a lower mean precipitation. Another interesting result of this study is the direct association between mean precipitation and COVID-19 incidence at high temperatures, but it has an inverse correlation in low temperate (P <0.05). This can be related to doing outdoor activities at high temperatures while at low temperatures people usually stay home and reduce close contact and thus reduce the spread of the virus. In line with our results, Sobral et al. (2020) found that precipitation has a positive correlation and SARS-CoV-2 transmission (Sobral et al. 2020).

Density population and COVID-19

Overall, there is a tendency that both incidence and death per capita rates increase with population density. The primary mechanism for the associations of population density on COVID-19 is probably associated with increased droplet and potentially airborne transmission in close contact (Bahl et al. 2020; Van Doremalen et al. 2020). We find that density has affected the timing of the outbreak in each county, with denser locations more likely to have an early outbreak. Several studies mention that population density is a dominant factor influencing the spread of SARS-CoV-2 (Bhadra et al. 2020; Rashed and Kodera 2020). We also found local authorities with high percentages of children (age between 0 and 15) had higher cases and death per capita rate of COVID-19. The study conducted by Dattner et al. (2021) revealed children had milder symptoms than adults when infected, which may have increased cases of COVID-19 (Dattner et al. 2021). This could be one of the reasons for the direct correlation between the percentage of children and increase in the disease.

Strengths and limitations

To the best of our knowledge, this is one of the most comprehensive studies of meteorological parameters on the incidence and death of COVID-19 at the local authority level. To date, scientific research of COVID-19 outcomes has been conducted at the country level, state level, and city level. There is a substantial difference between our current study and the previous research in the sense that this study examined all local authorities in the UK, whereas the other studies mostly employ data from select cities and are generalized for all of a country, especially in the US and in European countries (Bolaño-Ortiz et al. 2020; Coccia 2020; Coşkun et al. 2021; Gupta et al. 2020; Magnusson et al. 2020; Y. Wu et al. 2020). These types of studies have provided more detailed information to advance plausible predictions for incidence and death (cumulative and per capita rate), to recognize potential gaps in public health services such as hospital facilities, and to change or modify decision makers' perceptions toward environmental factors affecting the disease. Our local authority level analysis has allowed us to more holistically explore relevant contributions of median age, population density, and meteorological parameter changes on a given region's incidence and deaths associated with COVID-19. A strong innovation of our study is the ability to compare across the range of covariates for interaction effects—where the association with incidence and death rates runs in different directions at different levels of the variable. These findings can help to inform policy makers on the risk of COVID-19 transmission in different areas of a country. Further studies should be conducted, given that the COVID-19 variables will continue to change.

Despite the strengths of our study, there are several potential limitations in ecological studies which are known as "ecological fallacy." In these studies, researchers used variables that report the mean characteristics of groups in place of individual-level outcomes and are most useful in analyzing new hypotheses (Morgenstern 1995). Generalizability remains a potential concern, due to our focus on the local authority level. Lack of access to precise local meteorological data from a number of regions, which use meteorological stations data near the area, should be considered. Furthermore, out of a large number of possible factors that affect the incidence of and death from COVID-19, only meteorological were considered specific to the UK regions. However, caution should be taken in the extrapolation of the results beyond the UK region–based meteorological parameters entered in this study. Also, to determine the causal role of a variable as a risk factor, prospective studies such as longitudinal cohort should be designed, which we suggest in future research.

Conclusions

The primary results of this study reveal that wind speed, humidity, temperature, and population density may account for geographical variation in the spread of SARS-CoV-2 across the UK local authorities. It should be noted that weather parameters might have negative or positive effects on the transmission of COVID-19 in different conditions (such as warm or cold environments); however, we acknowledge that other parameters like people's behaviors or governments' regulations, quarantine schemes, and also interactions between climatic variables with each other could change the pattern of the disease. These findings may find relevant in policy decisions for prevention, control, and management of the COVID-19 pandemic, especially at the regional level throughout the countries.

Abbreviations COVID-19, coronavirus disease 2019; SARS-CoV, severe acute respiratory syndrome coronavirus; MERS-CoV, Middle East respiratory syndrome coronavirus; UK, United Kingdom; T, temperature; PC, proportion of case per million; PD, proportion of death per million

Availability of data and materials All data generated or analyzed during this study are included in this published article ("Material and methods") and publicly available dataset. Data related to the COVID-19 variables available on https://coronavirus.data.gov.uk website.

Author contribution Mohammad Sarmadi: conceptualization; methodology; data curation; formal analysis; writing—original draft preparation; writing—review and editing; supervision; funding acquisition. Darrick Evensen: methodology; formal analysis; writing—original draft preparation; writing—review and editing. Sajjad Rahimi: methodology; data curation; formal analysis; writing—original draft; writing—review and editing. Vahid Kazemi Moghaddam: conceptualization; data curation;

writing—original draft preparation. All authors read and approved the manuscript.

Declarations

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