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RESEARCH ARTICLE

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Visibility, wind speed, and dew point temperature are important factors in SARS-CoV-2 transmissibility

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Abstract

The aim of this study is to provide evidence for the influencing factors of severe acute respiratory syndrome coronavirus 2 (SARS-COV-2) virus mutation by determining the impact of geographical and meteorological factors on SARS-CoV-2 transmission, and the different impacts of SARS-CoV-2 variant strains. From January 20 to March 10, 2020, we collected a number of daily confirmed new cases and meteorological factors in all cities and regions in China and Italy affected by the Alpha "variants of concern" (VOC). We also collected the daily confirmed cases of the Delta VOC infection in China and Italy from May 21 to November 30, 2021. The relationships between daily meteorological data and daily verified new cases of SARS-CoV-2 transmission were then investigated using a general additive model (GAM) with a log link function and Poisson family. The results revealed that latitude was

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substantially connected with daily confirmed new instances of the Alpha VOC, while there was no such correlation with Delta VOC transmission. When visibility is greater than 7 m, the propagation of the Alpha and Delta VOCs in Italy and China can be controlled. Furthermore, greater temperatures and increased wind speed reduce the transmission of the Alpha and Delta VOCs. In conclusion, geographical and meteorological factors play an important role in SARS-CoV-2 transmissibility and should be considered in virus mitigation strategies.

KEYWORDS

Alpha VOC, Delta VOC, meteorological factors

INTRODUCTION

The first case of atypical pneumonia caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was reported in China on December 15, 2019.[1] With a significant number of reported cases and deaths, Italy was one of the first and most badly affected countries in Europe.[2] SARS-CoV-2 was found in Italy before the first imported cases which were identified in late January 2020.[2] The coronavirus disease 2019 (COVID-19) appears to be highly contagious, and it has been proven to be human-to-human transmissible for the first time, prompting the World Health Organization to declare it a pandemic.[3] The explosive epidemic has posed numerous difficulties in terms of diagnosis, prevention, and control. SARS-CoV-2 sublineages that pose the greatest threat (in terms of enhanced transmissivity, morbidity, or immune evasion) have been dubbed "variants of concern" (VOC). While Alpha (a.k.a. B.1.1.7 or "UK variant") was the dominant VOC in the first semester of 2020, a novel variant of SARS-CoV-2, the Delta variant of concern (VOC, also known as lineage B.1.617.2), is quickly becoming the dominant strain globally in the second semester on May 19, 2021, following massive vaccination campaigns.[4–6] By the end of May 2021, the Delta VOC had caused a new round of outbreaks in Guangdong Province[7] and subsequently spread to Italy.[5] An epidemiological study reveals that infection with the Delta VOC is associated with considerably increased transmissibility, viral loads, and illness progression risk as compared with the wild-type strain.[7]

A large number of studies, including fundamental research,[8] epidemiological investigations,[9,10] and mathematical models,[11] highlighted the emerging roles of weather variables in the transmission of the virus. The distribution of significant community outbreaks along restricted latitudes, temperatures, and humidity is consistent with that of a seasonal respiratory virus.[12] Ran et al.[13] reanalyzed ecological data sets of 154 Chinese cities and found that there is a nonlinear negative correlation between temperature and COVID-19 transmissibility.

Additionally, Mecenas et al.[14] found that warm and wet climates help decelerate the spread of COVID-19. Multiple pieces of research have demonstrated the critical function of meteorological data in transmission and infection. Thus, this study aims to further investigate the impact of environmental elements on the spread of SARS-CoV-2 variants (the Alpha and Delta VOC variants). We aim to determine whether geographical and meteorological conditions are influential factors in the spread of the COVID-19 pandemic. Based on the pathogens of two typical pneumonia outbreaks with similar biology homology,[14] this study aims to (1) assess the impact of geographical and meteorological factors on the transmission of SARS-CoV-2 and whether there are differences in the impact of different SARS-CoV-2 variant strains; and (2) determine whether the transmission model of SARS-CoV-2 virus includes geographical and meteorological factors so as to carry out large-scale environmental monitoring activities for SARS-CoV-2 transmission.

METHODS

Study population

The study populations are enrolled from the daily confirmed new cases of the Alpha VOC infection officially reported in sampled cities of China (31 cities) and Italy (21 cities) from January 20 to March 10, 2020, and the daily confirmed cases of the Delta VOC infection officially reported in China (5 cities) and Italy (18 cities) from May 21 to November 30, 2021. According to reports provided by the National Health Commission of China at all levels and the official website of Italian health authorities, the number of daily confirmed cases is an absolute number.

Meteorological and geographical data

From January 20 to March 10, 2020, and May 21 to November 30, 2021, daily meteorological data, including daily mean temperatures (°C), relative humidity (RH) (%), dew point temperature (DPT) (°C), visibility (meter), and mean wind speed (m/h), were collected from global meteorological data of China and Italy (http://www.wheata.cn/). Each city's latitude and longitude are contained in a global regional database.

Statistical analysis

Descriptive and correlation analyses were performed. Pearson's correlation coefficients are typically used for jointly normally distributed data (data that follows a bivariate normal distribution). A Spearman's correlation can be employed as a measure of a monotonic association for nonnormally distributed continuous data, ordinal data, or data containing meaningful outliers. Numerical variables were described with mean ± SD. Using the function general additive model (GAM) in the R package "mgcv," a smooth regression line of the meteorological variables on latitude and longitude was fitted, and this gradient pattern was then visualized. The distribution normality of daily meteorological data was tested by the Kolmogorov–Smirnov test, and collinearity among the meteorological variables was explored by the Spearman's (nonparametric data) or Pearson's (parametric data) tests with Scatter plots. To fully capture the whole information within this type of data, we implemented a new approach using GAMs, which were fitted using the "mgcv" package. GAMs are regression models that allow for the inclusion of nonparametric smoothing and will fit a regression spline to the data, allowing for nonlinear relationships. The level of complexity (nonlinearity) of each term of the model is determined by the estimated degrees of freedom (e.d.f.) of the smoother. An e.d.f. = 1 speaks of an almost linear relationship, while an e.d.f. > 1 indicates a nonlinear relationship.[15] Statistical significance was defined as $p < 0.05$.

All statistical analyses were conducted in SPSS and R 4.0.5, and the "ggplot2" package was used for visualization.[16]

RESULT

General characteristics of meteorological conditions in all cities

Table 1 shows the statistics for mean wind speed, visibility, DPT, mean temperature, RH, and daily confirmed cases infected by Alpha VOC in China and Italy in 2020. Table 2 illustrates the value of the above-mentioned weather circumstances as well as daily confirmed new Delta VOC instances in China and Italy in 2021.

The relationship between geographical distribution and COVID-19 transmissibility

We draw a map through longitude and latitude to show the geographical distribution of the cities affected by COVID-19. Simultaneously, the meteorological parameters of each city are marked on the map, and the gradient of environmental change is shown to better comprehend the relationship between the geographical/meteorological factors and the transmissibility of COVID-19 in different cities. The additive model's smooth regression is an excellent choice. We use the function GAM in the R packet "mgcv" to fit the smooth regression of climate variables with longitude and latitude geographical variables, and finally visualize this gradient model. The contour map and the 3D map respectively exhibit the smooth regression of climatic conditions in cities affected by COVID-19 with longitude and latitude geographical variables fitted by the additive model (the contour map is the projection style of the 3D map). The equidistant isolines for daily confirmed new cases of Alpha VOC

TABLE 1 General characteristics of meteorological data with all cities and regions of China/Italy affected by the Alpha VOC in 2020

	Mean wind speed (m/h)	Visibility (m)	Dew point temperature (°C)	Mean temperature (°C)	Relative humidity (%)	Daily new cases
China						
Beijing	4.90 ± 3.04	5.08 ± 1.65	−8.21 ± 4.62	0.53 ± 3.06	50.82 ± 17.35	9.40 ± 8.94
Chengdu	2.60 ± 0.73	6.27 ± 2.91	4.03 ± 2.88	8.41 ± 2.1	74.6 ± 11.41	4.58 ± 3.81
Dongguan	6.54 ± 2.52	7.54 ± 1.19	11.74 ± 6.02	17.48 ± 3.2	70.31 ± 14.9	3.19 ± 3.42
Fujian	6.26 ± 2.62	7.21 ± 2.65	8.3 ± 4.78	13.24 ± 2.89	73.00 ± 14.14	1.85 ± 1.99
Fuyang	5.00 ± 2.16	6.83 ± 3.57	1.45 ± 3.31	5.91 ± 3.67	73.88 ± 13.31	5.54 ± 3.89
Guangzhou	5.27 ± 3.18	5.56 ± 1.1	9.23 ± 5.93	16.08 ± 3.75	65.25 ± 15.2	9.89 ± 10.77
Kunming	8.06 ± 1.99	7.93 ± 1.73	2.13 ± 2.36	8.73 ± 2.71	65.04 ± 16.12	1.81 ± 1.89
Nanchang	3.01 ± 1.54	10.36 ± 5.35	4.63 ± 4.67	8.62 ± 3.08	77.32 ± 16.23	8.25 ± 6.26
Nanyang	4.84 ± 1.56	5.14 ± 4.63	−0.49 ± 4.62	5.21 ± 2.71	68.27 ± 19.28	6.04 ± 4.69
Shenzhen	6.71 ± 2.53	7.39 ± 1.27	11.03 ± 5.86	16.93 ± 2.95	69.53 ± 15.12	12.21 ± 13.41
Wenzhou	3.72 ± 1.02	6.67 ± 4.05	5.76 ± 5.43	10.61 ± 2.51	73.14 ± 16.87	17.07 ± 17.36
Hong Kong	3.31 ± 1.11	6.15 ± 0.77	13.33 ± 4.65	18.20 ± 2.67	73.90 ± 11.24	2.24 ± 2.22
Yinchuan	3.40 ± 1.84	8.27 ± 4.40	−12.92 ± 3.82	−0.67 ± 3.01	36.61 ± 12.80	1.46 ± 1.32
Yueyang	4.60 ± 2.32	6.15 ± 4.78	4.20 ± 4.34	8.09 ± 3.37	78.13 ± 17.21	5.57 ± 4.77
Zhangjiakou	4.96 ± 2.36	12.54 ± 5.40	−13.35 ± 4.74	−2.14 ± 4.31	38.79 ± 9.84	1.32 ± 1.76
Chongqing	2.82 ± 0.56	5.83 ± 2.97	5.13 ± 2.18	8.13 ± 1.74	81.73 ± 8.33	16.00 ± 10.62
Ezhou	4.66 ± 1.90	4.39 ± 1.47	4.03 ± 3.65	8.43 ± 3.77	74.87 ± 12.94	30.69 ± 39.37
Enshi	1.64 ± 0.51	8.57 ± 4.64	4.36 ± 2.41	8.36 ± 2.34	76.46 ± 9.06	8.66 ± 6.82
Huanggang	4.72 ± 2.34	5.53 ± 3.26	3.44 ± 4.02	8.05 ± 3.84	74.16 ± 16.03	66.70 ± 83.19
Huangshi	4.58 ± 1.98	4.67 ± 1.30	4.03 ± 3.83	8.65 ± 3.94	73.71 ± 12.67	25.68 ± 28.12
Jingmen	5.83 ± 2.00	6.10 ± 4.32	5.18 ± 4.22	8.86 ± 3.84	79.20 ± 15.85	25.00 ± 40.42
Jingzhou	3.90 ± 1.99	6.25 ± 3.62	5.06 ± 3.87	8.50 ± 3.61	79.74 ± 11.84	40.48 ± 59.09
Qianjiang	3.82 ± 2.00	6.76 ± 3.72	5.02 ± 4.22	8.91 ± 3.80	77.30 ± 11.55	5.91 ± 9.14
Shiyan	2.98 ± 1.39	7.95 ± 3.98	0.84 ± 3.75	6.24 ± 3.40	69.01 ± 14.08	17.66 ± 13.99
Suizhou	3.09 ± 1.09	5.16 ± 3.66	1.77 ± 3.99	7.94 ± 4.27	66.34 ± 15.08	38.35 ± 40.66
Tianmen	3.85 ± 2.05	6.70 ± 3.78	4.71 ± 4.12	8.60 ± 3.89	77.24 ± 11.39	15.45 ± 16.45
Wuhan	4.66 ± 1.90	4.39 ± 1.47	4.03 ± 3.65	8.43 ± 3.77	74.87 ± 12.94	1118.42 ± 2041.05
Xianning	4.42 ± 2.02	4.59 ± 1.34	2.82 ± 3.58	7.50 ± 3.32	73.20 ± 13.13	31.14 ± 40.16
Xiangyang	3.90 ± 1.47	8.67 ± 5.17	2.37 ± 4.40	6.55 ± 3.09	76.21 ± 17.77	38.71 ± 36.91
Xiaogan	4.72 ± 1.99	4.44 ± 1.41	3.99 ± 3.97	8.50 ± 4.10	74.37 ± 13.35	93.30 ± 95.15
Yichang	3.77 ± 0.68	5.80 ± 3.61	3.83 ± 3.98	8.30 ± 3.34	74.65 ± 14.98	26.28 ± 28.61
Italy						
Abruzzo	6.54 ± 2.50	6.20 ± 0.50	10.14 ± 2.92	3.69 ± 2.77	64.80 ± 13.64	29.04 ± 36.53
Basilicata	7.98 ± 3.50	5.16 ± 1.50	7.84 ± 4.07	4.52 ± 3.41	55.98 ± 18.16	4.91 ± 6.21
Bolzano	3.35 ± 1.53	6.15 ± 0.20	10.59 ± 3.45	2.90 ± 3.28	50.91 ± 16.20	42.85 ± 30.07
Calabria	5.83 ± 3.38	10.40 ± 2.18	10.40 ± 2.18	8.12 ± 2.07	62.68 ± 9.04	13.00 ± 13.81
Campania	7.34 ± 3.48	6.11 ± 0.18	14.41 ± 2.40	12.79 ± 2.57	53.85 ± 13.22	42.82 ± 45.52

TABLE 1 (Continued)

	Mean wind speed (m/h)	Visibility (m)	Dew point temperature (°C)	Mean temperature (°C)	Relative humidity (%)	Daily new cases
Emilia Romagna	5.91 ± 2.00	5.96 ± 0.54	9.49 ± 2.36	3.73 ± 2.53	61.81 ± 16.12	345.79 ± 292.84
Friuli V.G.	6.34 ± 3.84	6.20 ± 0.47	10.04 ± 2.33	6.65 ± 2.39	62.18 ± 21.22	45.56 ± 43.89
Lazio	6.20 ± 3.60	6.05 ± 0.32	13.59 ± 2.15	7.00 ± 3.36	56.25 ± 14.19	73.00 ± 68.69
Liguria	7.93 ± 2.41	6.30 ± 0.63	11.70 ± 1.76	8.22 ± 2.09	60.02 ± 19.37	80.83 ± 80.63
Lombardia	4.15 ± 1.96	5.66 ± 0.82	9.10 ± 2.60	3.58 ± 2.87	64.20 ± 16.34	1107.10 ± 822.92
Marche	6.43 ± 3.36	6.17 ± 0.41	9.75 ± 2.11	4.33 ± 2.53	67.19 ± 12.54	101.17 ± 82.43
Molise	10.84 ± 5.80	6.27 ± 0.18	0.48 ± 4.84	−2.16 ± 4.85	71.19 ± 16.94	3.17 ± 4.21
Piemonte	2.54 ± 0.79	6.06 ± 0.33	5.63 ± 2.58	−1.50 ± 3.66	62.49 ± 15.47	215.82 ± 229.30
Puglia	7.03 ± 2.44	6.16 ± 0.34	10.75 ± 2.63	5.20 ± 2.50	67.97 ± 10.01	39.04 ± 43.75
Sardegna	7.97 ± 2.62	6.25 ± 0.41	12.79 ± 1.73	7.87 ± 2.70	74.94 ± 9.46	19.22 ± 24.33
Sicilia	7.31 ± 4.54	5.50 ± 1.24	8.97 ± 3.01	6.63 ± 2.16	62.56 ± 18.86	18.63 ± 22.14
Toscana	4.84 ± 2.63	6.12 ± 0.53	10.28 ± 2.54	4.28 ± 2.98	66.23 ± 14.01	110.00 ± 101.93
Trento	7.22 ± 3.97	5.53 ± 2.31	−2.28 ± 4.42	−4.87 ± 4.09	67.64 ± 16.15	53.13 ± 56.23
Umbria	6.59 ± 3.36	6.01 ± 0.34	8.94 ± 2.68	3.40 ± 2.60	69.39 ± 11.29	28.40 ± 27.53
Veneto	6.54 ± 3.41	5.52 ± 1.54	9.19 ± 1.84	4.70 ± 2.44	69.64 ± 16.04	220.66 ± 187.59
Valle D'Aosta	4.01 ± 2.19	5.89 ± 0.84	7.91 ± 2.91	1.41 ± 2.45	55.36 ± 11.94	19.10 ± 19.74

Note: Values are given as mean ± SD.

Abbreviation: VOC, variants of concern.

were distributed along latitude and longitude, indicating that longitude and latitude are closely related to Alpha VOC transmission (Figure 1F). However, the equidistant isolines for daily confirmed new cases of Delta VOC were not distributed along latitude, suggesting that there is no significant correlation between latitude and Delta VOC transmission (Figure 2F). Meteorological variations associated with the geographic location are connected with latitude and longitude. The equidistant isolines of mean wind speed (Figures 1A and 2A), mean temperature (Figures 1C and 2C), DPT (Figures 1D and 2D), and RH (Figures 1E and 2E) are distributed evenly across latitude. Whereas the equidistant isolines of visibility (Figure 2B) are more visible along longitude.

In addition, Spearman's (nonparametric data) and Pearson's (parametric data) correlation analysis was utilized to investigate the relationship between latitude and longitude and COVID-19 transmission, without considering differences in epidemic prevention and control strategies among countries. The results revealed that latitude was substantially connected with daily confirmed new cases of the Alpha VOC ($r = 0.536$, $p < 0.001$) (Figure 3A, a), indicating that higher latitude from the equator is associated with more daily confirmed new cases of the Alpha VOC. Similarly, longitude was dramatically correlated with daily confirmed new cases of the Alpha VOC ($r = -0.450$, $p = 0.001$) (Figure 3A, b) and daily confirmed new cases of the Delta VOC ($r = -0.476$, $p = 0.022$) (Figure 3B, b), implying that the local topography determined by longitude can affect the climate, thereby influencing the spread of the SARS-CoV-2 transmission. It is worth noting that latitude did not correlate with daily confirmed new cases of the Delta VOC ($r = 0.108$, $p = 0.625$) (Figure 3B, a), indicating that latitude only made a difference in the SARS-CoV-2 Alpha VOC and not the SARS-CoV-2 Delta VOC.

As China and Italy have different COVID-19 prevention and control tactics, we investigated whether latitude and longitude differentially affect the spread of the SARS-CoV-2 virus under epidemic control measures in different countries. Our findings indicated that daily confirmed new cases of the Alpha VOC in Italy were remarkably related to latitude ($r = 0.568$, $p = 0.007$) (Figure 3C, a) and longitude ($r = -0.529$, $p = 0.014$) (Figure 3C, b). But there was no significant relationship between daily confirmed new cases of the Delta VOC in Italy (Figure 3D, a and b), suggesting the potential influence of geographic distribution on Alpha VOC transmission. Yet geographic distribution was not associated with Delta VOC transmission in Italy. In China, however, Alpha VOC transmission was not

TABLE 2 General characteristics of meteorological data with Chinese/Italian cities and regions affected by the Delta VOC in 2021

City/province	Mean wind speed (m/h)	Visibility (m)	Dew point temperature (°C)	Mean temperature (°C)	Relative humidity (%)	Daily new cases
China						
Putian	8.58 ± 2.95	11.47 ± 4.81	16.48 ± 1.71	19.28 ± 0.92	84.31 ± 9.20	20.35 ± 20.85
Guangzhou	5.83 ± 1.57	6.49 ± 0.53	24.44 ± 1.37	29.39 ± 2.13	75.34 ± 9.49	5.28 ± 4.40
Heihe	5.19 ± 2.68	15.10 ± 5.21	−8.07 ± 5.69	−1.49 ± 4.59	59.65 ± 17.68	17.93 ± 13.07
Harbin	4.61 ± 1.77	13.21 ± 4.19	7.97 ± 5.54	13.03 ± 3.21	72.43 ± 15.15	5.93 ± 4.62
Nanjing	6.39 ± 2.12	7.00 ± 1.67	24.45 ± 1.00	28.44 ± 1.45	79.57 ± 9.77	10.22 ± 12.67
Italy						
Abruzzo	5.48 ± 1.46	6.01 ± 0.53	13.36 ± 3.84	20.37 ± 5.33	65.84 ± 14.14	70.6 ± 53.64
Bolzano	3.13 ± 1.39	6.13 ± 0.32	9.16 ± 5.16	18.05 ± 7.05	58.78 ± 17.09	81.45 ± 112.65
Calabria	7.79 ± 2.99	6.01 ± 0.40	13.02 ± 3.56	21.03 ± 4.79	62.52 ± 15.52	153.56 ± 89.63
Campania	4.74 ± 1.64	6.22 ± 0.28	13.74 ± 4.14	21.75 ± 4.97	61.59 ± 11.77	451.93 ± 323.24
Emilia Romagna	5.12 ± 1.19	5.98 ± 1.18	11.92 ± 4.06	19.84 ± 6.37	62.38 ± 15.46	384.79 ± 245.28
Friuli V.G.	2.9 ± 3.5	6.2 ± 0.7	13.99 ± 6.17	21.32 ± 5.89	64.17 ± 12.93	120.94 ± 171.67
Lazio	6.02 ± 1.96	6.04 ± 0.43	13.35 ± 4.81	23.31 ± 6.95	55.65 ± 14.48	466.43 ± 310.11
Liguria	7.71 ± 3.8	6.58 ± 0.43	14.65 ± 5.66	20.3 ± 4.65	71.1 ± 13.29	173.32 ± 970.13
Lombardia	3.67 ± 1.2	5.73 ± 0.98	12.68 ± 4.65	18.96 ± 6.12	68.55 ± 14.4	660.52 ± 528.59
Marche	5.26 ± 2.2	5.99 ± 0.56	13.08 ± 3.7	20.39 ± 5.91	65.3 ± 16.46	115.72 ± 99.96
Molise	5.47 ± 3.41	5.75 ± 1.13	13.28 ± 5.71	19.84 ± 6.92	69.39 ± 20.25	9.3 ± 10.63
Piemonte	2.93 ± 1.78	5.69 ± 1.11	10.91 ± 5.16	20.35 ± 6.36	57.19 ± 17.37	250.54 ± 200.12
Sardegna	7.33 ± 2.08	6.27 ± 0.33	15.55 ± 4.16	21.79 ± 4.85	68.63 ± 10.94	137.23 ± 361.28
Sicilia	8.07 ± 2.96	6.17 ± 0.1	16.66 ± 3.81	23.17 ± 4.34	67.63 ± 9.85	539.16 ± 350.48
Trento	7.87 ± 4.23	5.37 ± 2.68	4.1 ± 7.23	10.38 ± 8.2	68 ± 20.31	37.91 ± 32.85
Umbria	6.16 ± 2.18	6.1 ± 0.42	11.6 ± 3.22	19.56 ± 5.87	62.48 ± 16.43	61.08 ± 45.12
Veneto	5.89 ± 1.79	6.11 ± 1	13.15 ± 5.16	18.96 ± 5.84	69.89 ± 10.43	491.86 ± 424.43
Valle D'Aosta	6.36 ± 3.14	6.12 ± 0.33	7.99 ± 5.9	17.85 ± 6.45	54.99 ± 17.38	10.57 ± 14.93

Note: Values are given as mean ± SD.

Abbreviation: VOC, variants of concern.

significantly correlated with latitude (Figure 3C, a) and longitude (Figure 3C, b), while Delta VOC transmission was not significantly correlated with latitude (Figure 3D, a) and longitude (Figure 3D, b).

The association between meteorological conditions

The Kolmogorov–Smirnov test was then used to determine the distribution normality of daily meteorological data. The Spearman's (nonparametric data) and Pearson's (parametric data) tests were used to investigate collinearity between meteorological variables using Scatter plots. Collinear meteorological variables were not included in the model at the same time. In Figure S1a,b, scatter plots and linear regressions depict the correlation between daily meteorological data in China from January 20 to March 10, 2020, and in Italy from May 21 to November 30, 2021. We discovered that most cities or countries had a collinearity between mean temperature and DPT, as shown in Figure S1.

Meteorological modeling

We used GAM with log link function and Poisson family to explore the associations between daily meteorological

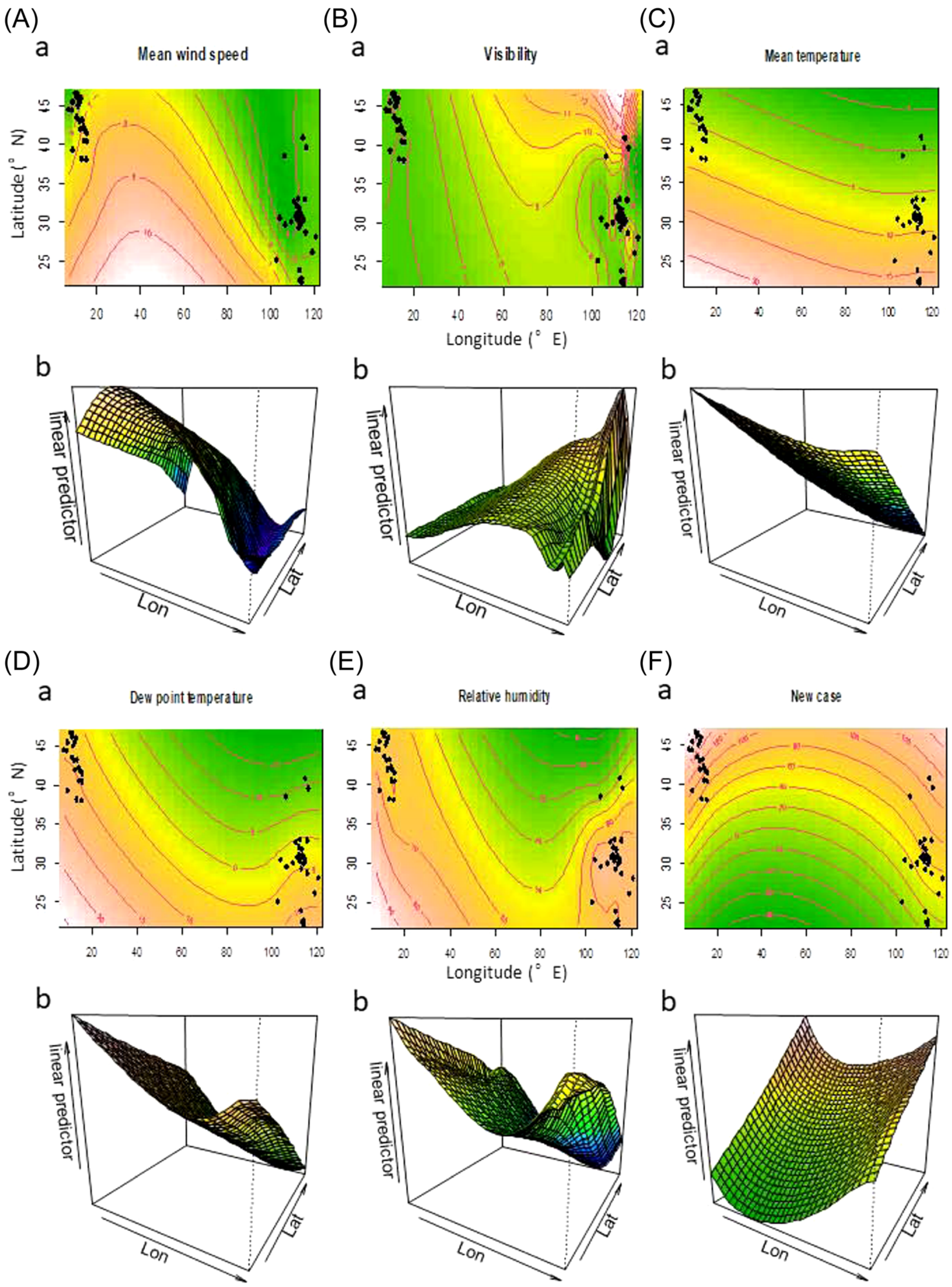

FIGURE 1 Smooth regressions of meteorological factors and daily new cases of the Alpha "variants of concern" with geographical variables in contour and 3D plots. (A–F) Smooth regression of mean wind speed, visibility, mean temperature, dew point temperature, relative humidity, and daily new case with latitude and longitude. Each line in the contour map reflects the value of the index (meteorological factors or daily new cases), and the difference between the values of neighboring lines is equal. The index value becomes more concentrated as the isoline density increases. Longitude is represented by the horizontal and vertical axes, latitude is represented by the vertical axis, and the geographical position of Chinese and Italian cities is shown by the circle

data and daily confirmed new cases as daily confirmed new cases roughly followed a Poisson distribution. Furthermore, the relationships between new confirmed cases and meteorological data were largely nonlinear.

Without taking into account differences in epidemic prevention and control strategies between countries, we discovered a significant association between meteorological data and new confirmed SARS-CoV-2 cases in 2020 and 2021. As shown in Figure 4 (Alpha, d and Delta, d), when visibility is greater than 7 m, there is a nonlinear negative correlation between visibility and daily confirmed new cases of the Alpha VOC (e.d.f. = 10.668, $p < 0.0001$) and the Delta VOC (e.d.f. = 2.955, $p < 0.0001$), implying that higher visibility may suppress the transmission of COVID-19

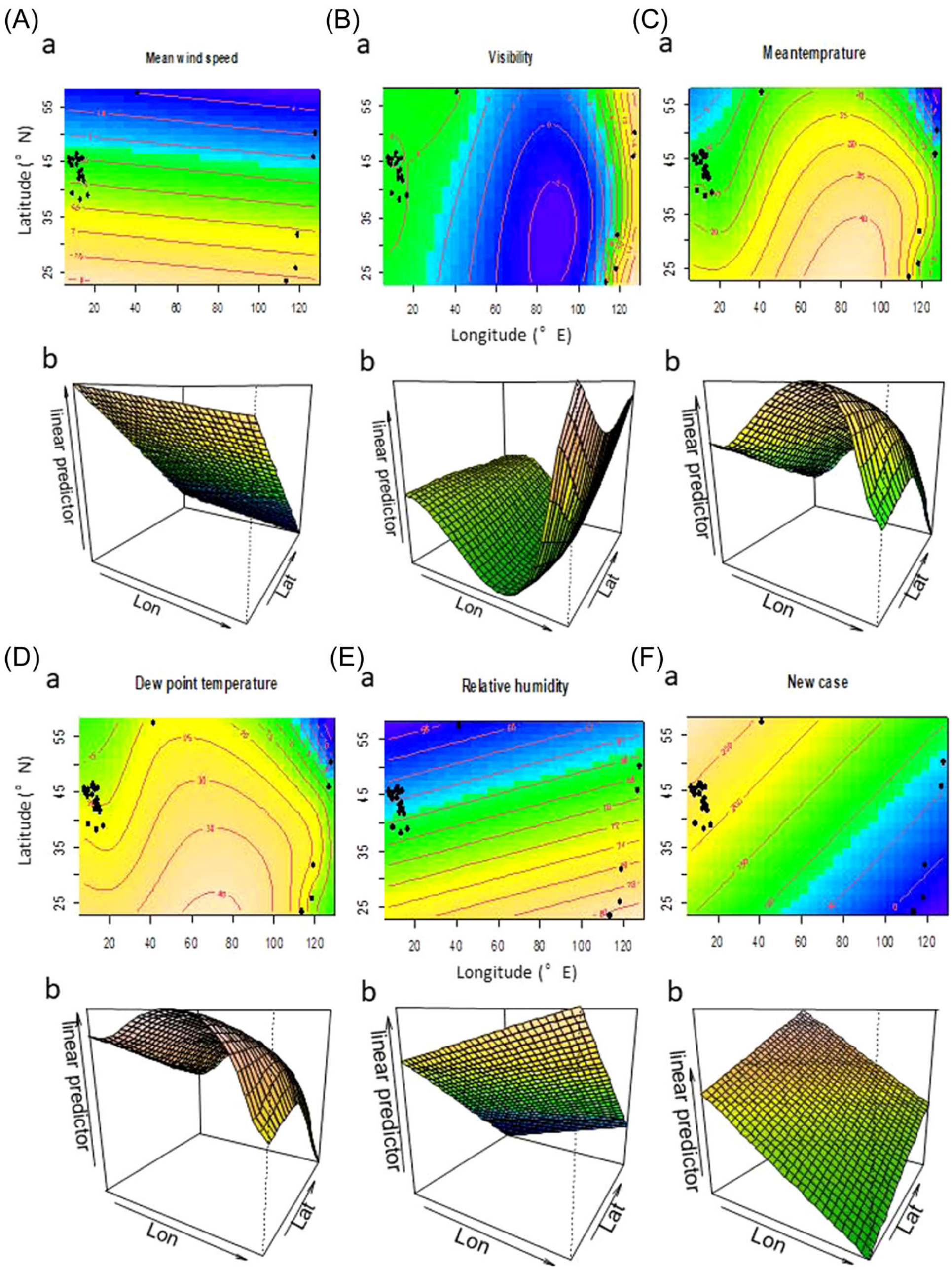

FIGURE 2 Smooth regressions of meteorological factors and daily new cases of the Delta "variants of concern" with geographical variables in contour and 3D plots. (A–F) Smooth regression of mean wind speed, visibility, mean temperature, dew point temperature, relative humidity, and daily new case with latitude and longitude. Each line in the contour map reflects the value of the index (meteorological factors or daily new cases), and the difference between the values of neighboring lines is equal. The index value becomes more concentrated as the isoline density increases. Longitude is represented by the horizontal and vertical axes, latitude is represented by the vertical axis, and the geographical position of Chinese and Italian cities is shown by the circle

transmissibility. Surprisingly, we discovered that DPT greater than 17°C reduces Alpha VOC transmission (e.d.f. = 11.127, $p < 0.0001$) (Figure 4 [Alpha, b]), whereas DPT greater than 22°C slows Delta VOC transmission (e.d.f. = 1.001, $p < 0.0001$) (Figure 4 [Delta, b]). RH has little effect on the daily confirmed new cases of SARS-CoV-2 (Figure 4 [Alpha, c and Delta, c]).

We further examined if the impact of weather conditions on the spread of the SARS-CoV-2 virus changed according to different outbreak prevention and control strategies in China and Italy. When the average wind speed is greater than 11 m/h, there is a significant nonlinear negative correlation between the daily new cases of Alpha VOC (e.d.f. = 11.571,

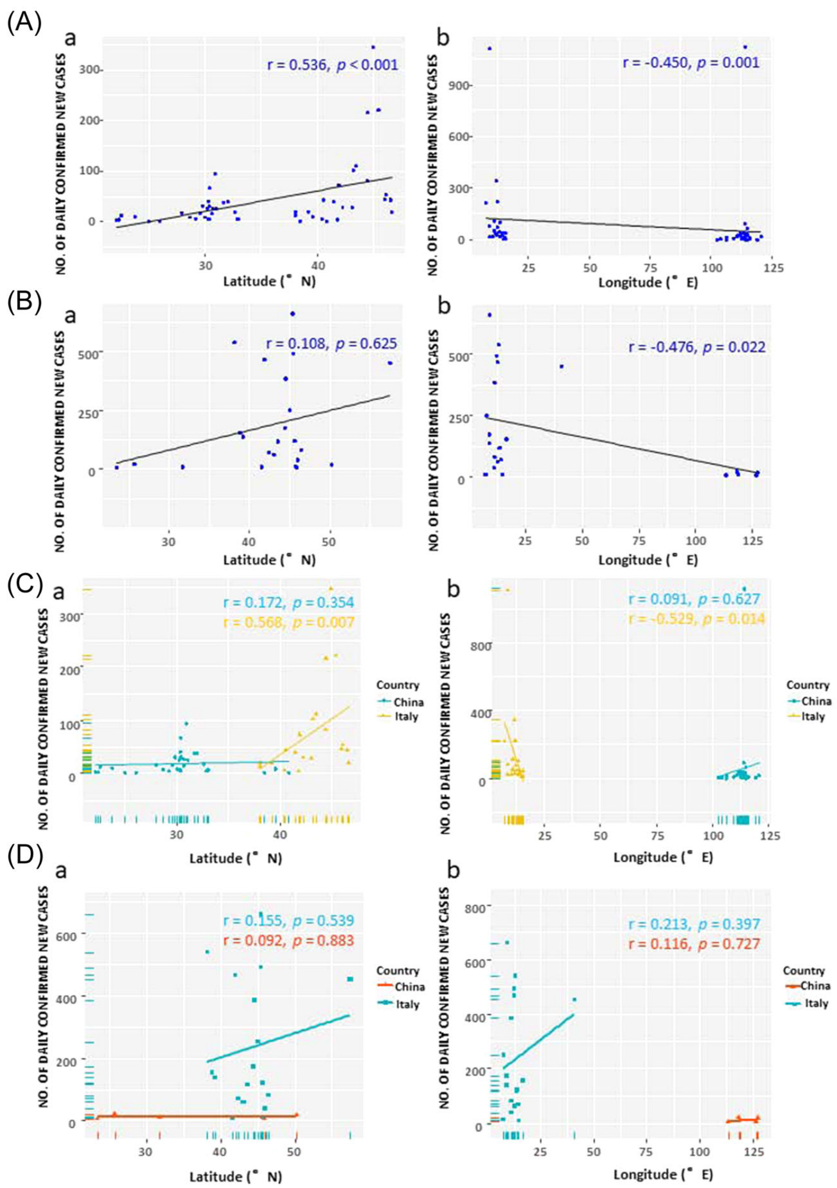

FIGURE 3 Linear regression against latitude and longitude was used to examine daily new cases of the Alpha "variants of concern" (VOC) in 52 sample cities and daily new cases of the Delta VOC in 23 representative cities in China and Italy. (A–a) Linear regression of daily new cases of the Alpha VOC in China and Italy with latitude. (A–b) Linear regression of daily new cases of the Alpha VOC in China and Italy with longitude. (B–a) Linear regression of daily new cases of the Delta VOC in China and Italy with latitude. (B–b) Linear regression of daily new cases of the Delta VOC in China and Italy with longitude. (C–a) Linear regression of daily new cases of the Alpha VOC in China and Italy with latitude, respectively. (C–b) Linear regression of daily new cases of the Alpha VOC in China and Italy with longitude, respectively. The blue circles represent 31 cities in China. The orange circles represent 21 cities in Italy. (D–a) Linear regression of daily new cases of the Delta VOC in China and Italy with latitude, respectively. (D–b) Linear regression of daily new cases of the Delta VOC in China and Italy with longitude, respectively. The red circles represent five cities in China. The blue circles represent 18 cities in Italy

$p < 0.0001$) (Figure 5 [Alpha, a]) and Delta VOC (e.d.f. = 4.288, $p = 0.0002$) (Figure 5 [Delta, a]) and the wind speed in China. Interestingly, there is a nonlinear negative association between RH and daily new cases of the Alpha VOC when RH is higher than 90% (e.d.f. = 13.346, $p < 0.0001$) (Figure 5 [Alpha, c]), while higher RH contributes to the Delta VOC transmissibility (e.d.f. = 1.000, $p = 0.0002$) (Figure 5 [Delta, c]) in China. Similarly, greater DPT (Figure 5 [Alpha, b]) and higher visibility (Figure 5 [Alpha, d]) may suppress the transmission of the Alpha VOC transmissibility in China, whereas DPT (Figure 5 [Delta, b]) and visibility (Figure 5 [Delta, d]) have a significantly weakened influence on Delta VOC propagation. The relationship between meteorological conditions and SARS-CoV-2 transmission in Italy was then investigated further. The spread of the Alpha VOC (e.d.f. = 8.986,

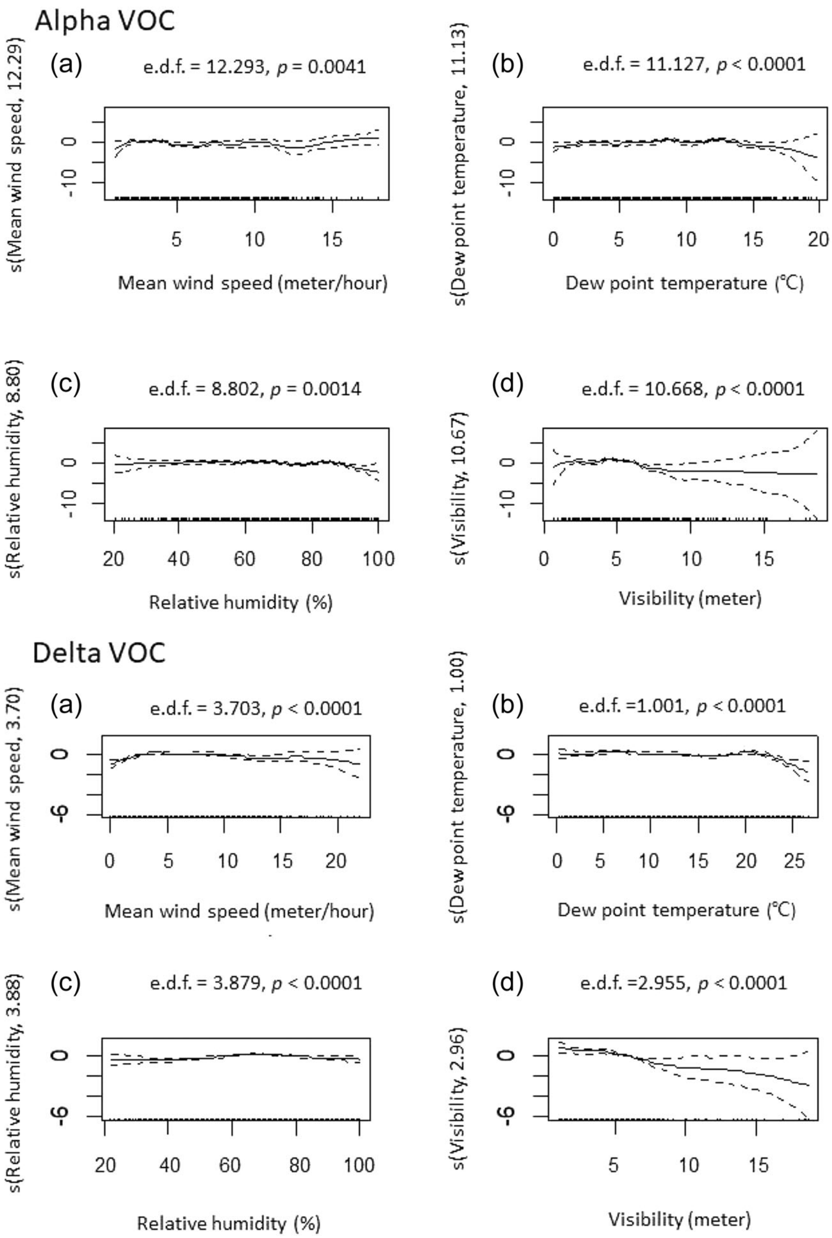

FIGURE 4 General additive model (GAM) with log link function and Poisson family was employed to explore the associations between daily meteorological data and daily confirmed new cases of the Alpha "variants of concern" (VOC) in 52 cities and the Delta VOC in 23 cities in China and Italy. Alpha (a–d) GAM modeling of the relationship between mean wind speed, dew point temperature, relative humidity, visibility, and daily confirmed new cases of the Alpha VOC. Delta (a–d) GAM modeling of the relationship between mean wind speed, dew point temperature, relative humidity, visibility, and daily confirmed new cases of the Delta VOC. Each panel shows the smooth fit of the common trend, and the "s" on the ordinate represents the smoother. The level of complexity (nonlinearity) of each term of the model is determined by the estimated degrees of freedom (e.d.f.) of the smoother. The area between the two dotted lines is the 95% confidence interval of the fitted smoothers

$p < 0.0001$) (Figure 6 [Alpha, a]) and the Delta VOC (e.d.f. = 9.176, $p < 0.0001$) (Figure 6 [Delta, a]) can be reduced when the mean wind speed is greater than 18 m/h. Similarly, increased visibility inhibited the propagation of the Alpha VOC (Figure 6 [Alpha, d]) and the Delta VOC (Figure 6 [Delta, d]). Changes in DPT (Figure 6 [Delta, b]) and RH (Figure 6 [Delta, c]) on Delta transmission, on the other hand, were much weaker.

DISCUSSION

Our findings suggested that latitude affects the spread of SARS-CoV-2 Alpha VOC but not Delta VOC, probably because the higher transmission rates, viral load, and risk of disease progression associated with Delta VOC infection[7] masked the effect of latitude on Delta VOC transmission. In the grouping analysis of the two countries, the results of Italy are consistent with the overall results, while there is no correlation between latitude and the Alpha VOC transmission in China. This may be due to the earlier adoption of a stricter closure policy in China, which resulted in the number of newly diagnosed cases of the Alpha VOC being mainly concentrated in Wuhan and its nearby areas, leading to biased data sources.

As previously reported, respiratory droplets and physical contact are the main transmission routes for the person-to-person spread of SARS-CoV-2.[17] Airborne transmission of disease can occur through large droplets

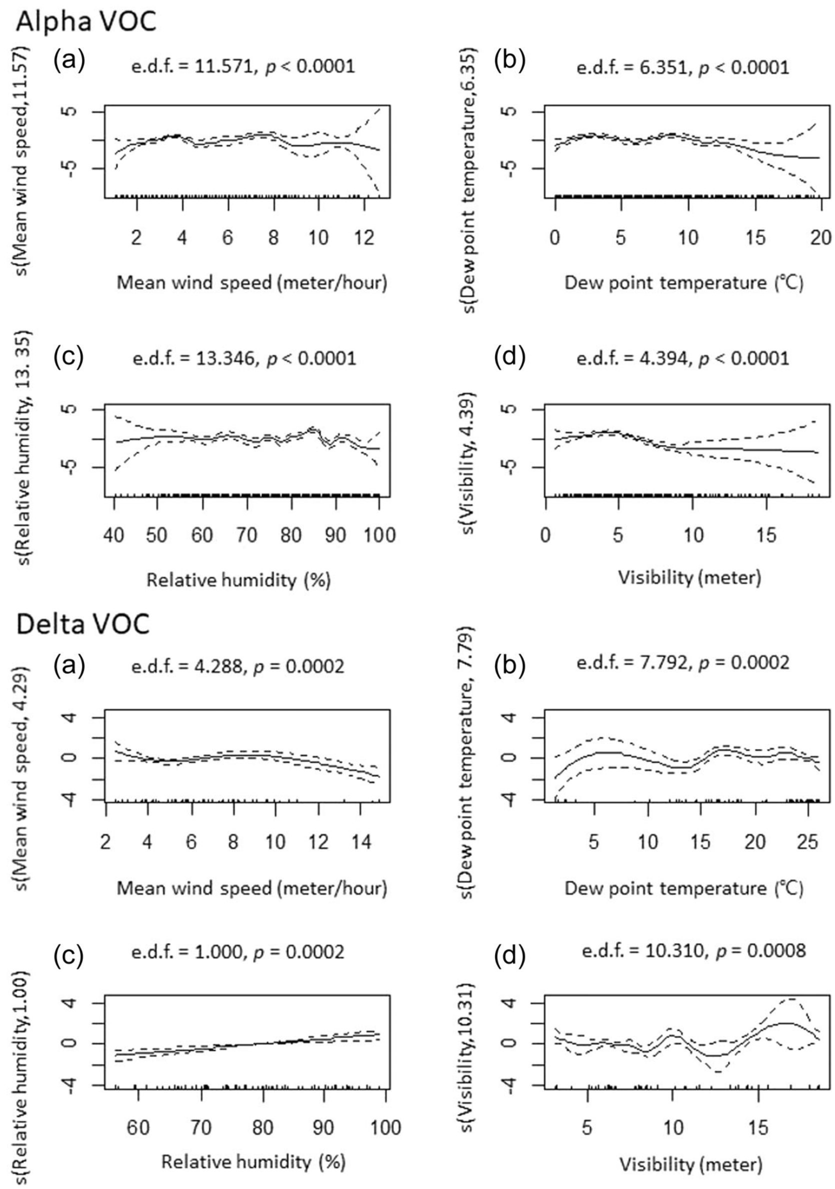

FIGURE 5 General additive model (GAM) with log link function and Poisson family was employed to explore the associations between daily meteorological data and daily confirmed new cases of the Alpha "variants of concern" (VOC) in 31 cities and the Delta VOC in 5 cities in China. Alpha (a–d) GAM modeling of the relationship between mean wind speed, dew point temperature, relative humidity, visibility, and daily confirmed new cases of the Alpha VOC. Delta (a–d) GAM modeling of the relationship between mean wind speed, dew point temperature, relative humidity, visibility, and daily confirmed new cases of the Delta VOC. Each panel shows the smooth fit of the common trend, and the "s" on the ordinate represents the smoother. The level of complexity (nonlinearity) of each term of the model is determined by the estimated degrees of freedom (e.d.f.) of the smoother. The area between the two dotted lines is the 95% confidence interval of the fitted smoothers

(>5 μm) produced by infectious agents during breathing, coughing and sneezing, or by solid residues of small droplets (<5 μm) (known as droplets cores or aerosols).[18] Greenhalgh et al.[19] proposed 10 scientific reasons in support of the hypothesis that SARS-CoV-2 is transmitted primarily through the air. Moreover, studies have shown that indoor environments have higher concentrations of virus-laden aerosols than outdoor environments.[20] This is consistent with our finding that higher mean wind speeds can suppress the spread of the Alpha VOC and the Delta VOC, indicating that strong winds that favor dilution of virus-laden aerosols or influence the concentrations of virus-laden particles in outdoor air. As a result, keeping a fresh flow of indoor air and frequent ventilation can help to enhance the indoor environment and reduce the transmission of SARS-CoV-2.

It is noteworthy that Setti et al.[21] demonstrated that SARS-CoV-2 RNA can be present in atmospheric particulate matter (PM), and that SARS-CoV-2 can form clusters with outdoor PM under conditions of atmospheric stability and high PM concentrations, enhancing viral persistence in the atmosphere. In addition, particulate matter pollution can impair visibility, making visibility an important proxy for particulate matter pollution. Interestingly, we found that higher visibility levels resulted in the decreased transmission of the Alpha VOC and the Delta VOC, illustrating that lower visibility reflects the increase in particle pollutant emissions. And virus-carrying aerosols can interact with atmospheric particles to form clusters. The original particles serve as carriers to enhance the persistence of the virus in the atmosphere, thus promoting the spread of the

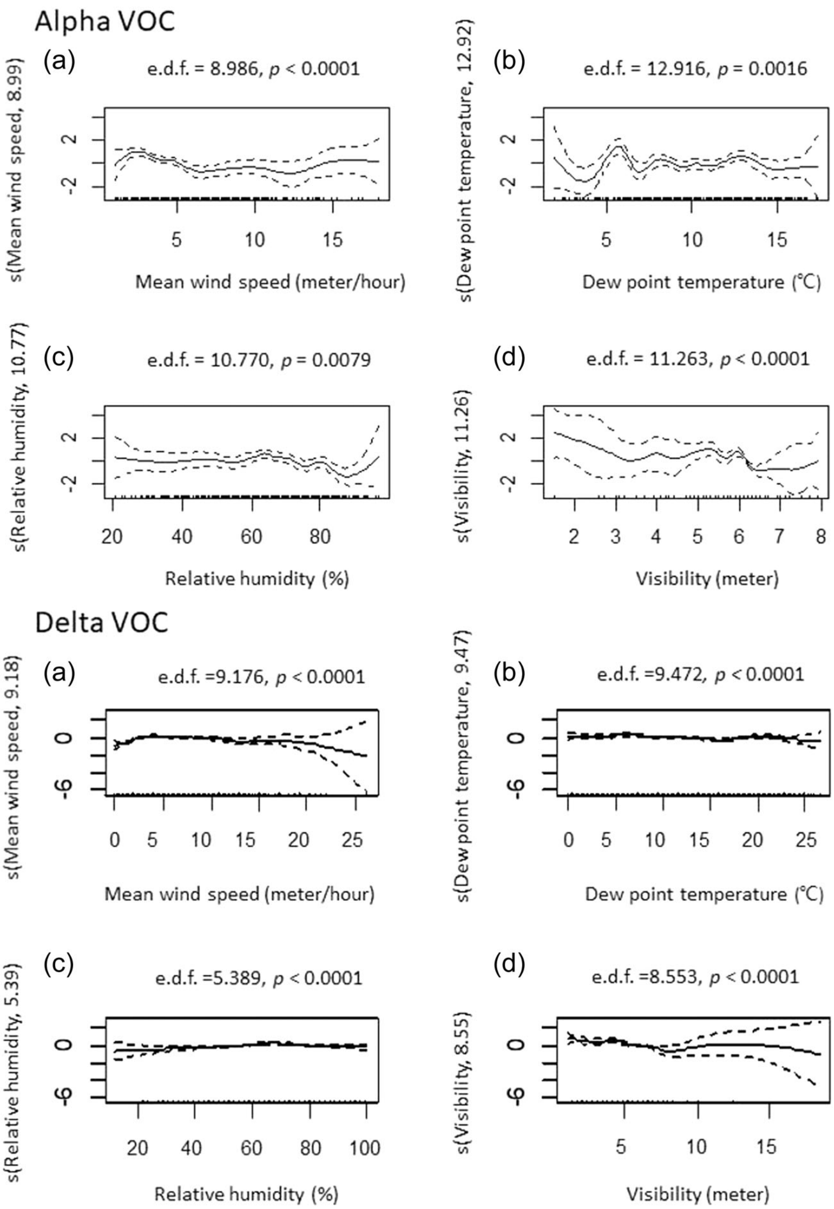

FIGURE 6 General additive model (GAM) with log link function and Poisson family was employed to explore the associations between daily meteorological data and daily confirmed new cases of the Alpha "variants of concern" (VOC) in 21 cities and the Delta VOC in 18 cities in Italy. Alpha (a–d) GAM modeling of the relationship between mean wind speed, dew point temperature, relative humidity, visibility, and daily confirmed new cases of the Alpha VOC. Delta (a–d) GAM modeling of the relationship between mean wind speed, dew point temperature, relative humidity, visibility, and daily confirmed new cases of the Delta VOC. Each panel shows the smooth fit of the common trend, and the "s" on the ordinate represents the smoother. The level of complexity (nonlinearity) of each term of the model is determined by the estimated degrees of freedom (e.d.f.) of the smoother. The area between the two dotted lines is the 95% confidence interval of the fitted smoothers

SARS-CoV-2. Furthermore, Visibility was also found to be strongly connected with ultraviolet (UV) radiation, which has the potential to deteriorate the virus and shorten its time in the atmosphere.[22]

Moreover, our findings further demonstrate that the DPT is negatively associated with the transmissibility of the Alpha VOC and the Delta VOC in a warmer environment, implying that the virus requires specific DPT conditions to survive and that increasing DPT reduces their ability to spread. Strikingly, we discovered that higher RH inhibited the transmission of the Alpha VOC, while elevated RH contributed to the growth and transmission of the Delta VOC. Humidity is becoming more widely recognized as a factor in aerosol transmission.[23] On the one hand, as the RH or temperature rises, the number of aerosol nuclei produced decreases, and virus survival increases.[23] On the other hand, some enveloped viruses have been shown to be stable at medium and high RH.[24,25] Because increased humidity decreases the number of droplet nuclei formed, and the same mechanism (decreased droplet evaporation and faster droplet sedimentation) results in deposition of larger mass respiratory droplets on the surface,[23] leaving the concentration of solutes in the droplets relatively unchanged and thus protecting against viruses.[23] However, further research will be needed to determine the significance of RH in SARS-CoV-2 transmission.

These results indicate that SARS-CoV-2 transmission would be low during high visibility, strong wind, and elevated DPT. Consequently, we propose that the macroscopic regulation of pollution emissions, reduced PM interactions with virus-laden aerosols, and the formation of air circulation both indoors and outdoors through fenestration ventilation improve the indoor environment, dilute virus particles concentrations, and thus inhibit the SARS-CoV-2 transmission.

In conclusion, geographical and meteorological factors play a significant role in SARS-CoV-2 transmissibility and should be taken into account when developing virus mitigation strategies. Finally, integrating the environmental impact into the SARS-CoV-2 transmission model and performing large-scale SARS-CoV-2 transmission environmental monitoring activities in public places in many countries may help to contain the COVID-19 pandemic.

AUTHOR CONTRIBUTIONS

Drs. Dansha Zhou, Elizabeth W. Wang, Chi Hou, Jing Liao, and Jiarui Zhang had full access to all the data in the study. They took responsibility for the integrity of the data and the accuracy of the data analysis. *Concept and design*: Drs. Dansha Zhou, Elizabeth W. Wang, Chi Hou, Jing Liao, Jiarui Zhang, Xin Fu, and Jiyuan Chen. *Acquisition, analysis, or interpretation of data*: All authors. *Drafting of the manuscript*: Drs. Dansha Zhou, Elizabeth W. Wang, Chi Hou, and Jing Liao. *Critical revision of the manuscript for important intellectual content*: All authors. *Statistical analysis*: All authors. *Administrative, technical, or material support*: Drs. Elizabeth W. Wang and Jiyuan Chen. All authors contributed to data interpretation, manuscript writing, and critical analysis of the manuscript; and provided final approval for manuscript submission.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

ETHICS STATEMENT

Ethics statement is not applicable to this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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