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Predicting SARS-CoV-2 weather-induced seasonal virulence from atmospheric air enthalpy

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Abstract: Following the coronavirus disease 2019 (COVID-19) pandemic, several studies have examined the possibility of correlating the virulence of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus that causes COVID-19, to the climatic conditions of the involved sites; however, inconclusive results have been generally obtained. Although either air temperature or humidity cannot be independently correlated with virus viability, a strong relationship between SARS-CoV-2 virulence and the specific enthalpy of moist air appears to exist, as confirmed by extensive data analysis. Given this framework, the present study involves a detailed investigation based on the first 20–30 days of the epidemic before public health interventions in 30 selected Italian provinces with rather different climates, here assumed as being representative of what happened in the country from North to South, of the relationship between COVID-19 distributions and the climatic conditions recorded at each site before the pandemic outbreak. Accordingly, a correlating equation between the incidence rate of the pandemic and the average specific enthalpy of atmospheric air was developed, and an enthalpy-based seasonal virulence risk scale was proposed as a tool to predict the potential danger of COVID-19 spread due to the persistence of weather conditions favorable to SARS-CoV-2 viability. For practical applications, a conclusive risk chart expressed in terms of coupled temperatures and relative humidity (RH) values was provided, showing that safer conditions occur in case of higher RH at the highest temperatures, and of lower RH at the lowest temperatures. The proposed risk scale was in agreement with the available infectivity data in the literature for a number of cities around the world.

Keywords: weather-related SARS-CoV-2 virulence; specific enthalpy of atmospheric moist air; temperature and humidity effects on COVID-19 outbreak; correlating equation; COVID-19 spread prediction risk scale

1. Introduction

Temperature and humidity play a key role in the survival of a number of viruses, including severe acute respiratory syndrome coronavirus (SARS-CoV), Middle East respiratory syndrome-related coronavirus (MERS-CoV), and the influenza viruses [1 - 7], to which SARS-CoV-2 has recently been added [8]. In a previous work we noted that, although temperature or humidity cannot be independently correlated with virus viability, a strong relationship between virus survival and the specific enthalpy of moist air, hereafter denoted as h , appears to exist [9]. In fact, according to the analyzed data, when the environmental conditions are such that the h value falls within the range of 50 and 60 kJ/kg dry air, virus survival decreases dramatically. In contrast, data on h values, which may potentially be responsible for magnification of SARS-CoV-2 infectivity rather than inactivation, have not yet been investigated extensively despite an increasing but inconclusive number of studies that suggest geographic and climatic influences on coronavirus disease 2019 (COVID-19) outbreaks and spread [10 - 18]. Since human coronaviruses have generally shown a marked winter seasonality [19 - 23], the atmospheric h value at ground level may be tentatively used as a synthetic state property involving overall heat (sensible + latent) to evaluate the role of climate as a factor influencing the viability and diffusion of SARS-CoV-2, which is the scope of the present investigation.

For the sake of realism, a preliminary statement related to the accuracy of the results is worth mentioning. Since any investigation combining climatic events with epidemiological events unavoidably crosses and merges two universes of empirical data, each of which is separately characterized by a high rate of uncertainty when compared to other fields of science or technology, the expected level of accuracy of the correlating results from this type of a study is not particularly

high. Moreover, such a tribute to natural complexity is a challenge that we have confronted in full awareness. This in order to acquire not only meaningful results, as solicited since February 2020 by the World Health Organization (WHO) when among the knowledge gaps mentioned the “epidemic’s relation to seasonality” [24], but also the limitations and implications of their applicability.

2. Materials and methods

A study involving a comparison of the climate data from many cities around the world with and without significant community transmission was recently carried out by Sajadi et al. [25]. It was found that areas with higher COVID-19 progression were distributed roughly along the 30°–50° North latitude corridor and experienced consistently similar weather patterns in terms of average air temperature around 7 °C and specific humidity around 5 grv/kg, which correspond to an average relative humidity (RH) of approximately 80%, as recorded by local airport weather stations 20–30 days prior to the first fatal COVID-19 cases. However, the epidemiological threat was identified in terms of absolute numbers of either deaths or infected people regardless of the percent incidence within the total population, and no attempt was made to define a unique climatic parameter that could be directly correlated with virus strength. The results are reorganized in Fig. 1, in which we used absolute humidity (AH) instead of specific humidity as originally done by the authors of the cited investigation. The size of each circle represents the total number of COVID-19 cases declared in each city and the red color is used to denote eight cities (namely Wuhan, Tokyo, Daegu, Qom, Milan, Seattle, Paris, and Madrid) where a significant number of deaths occurred before March 10, 2020, which was the last day of data collection.

Based on these data, we proposed an elaboration by introducing the COVID-19 incidence rate (IR), which was calculated as the ratio between the number of ascertained cases and the total population of any of the cities included in the comparative analysis, and using the value of the thermodynamic potential h to provide an effective synthetic representation of the thermo-hygrometric state of atmospheric air at ground level.

Subsequently, owing to the limited amount of data available for cities in which significant community transmission of COVID-19 occurred, the analysis was extended to a wider number of Italian provinces. This allowed us to propose an h -related risk scale, together with a temperature-RH chart, to simplify the prediction of non-negligible danger of SARS-CoV-2 virulence because of favorable weather conditions.

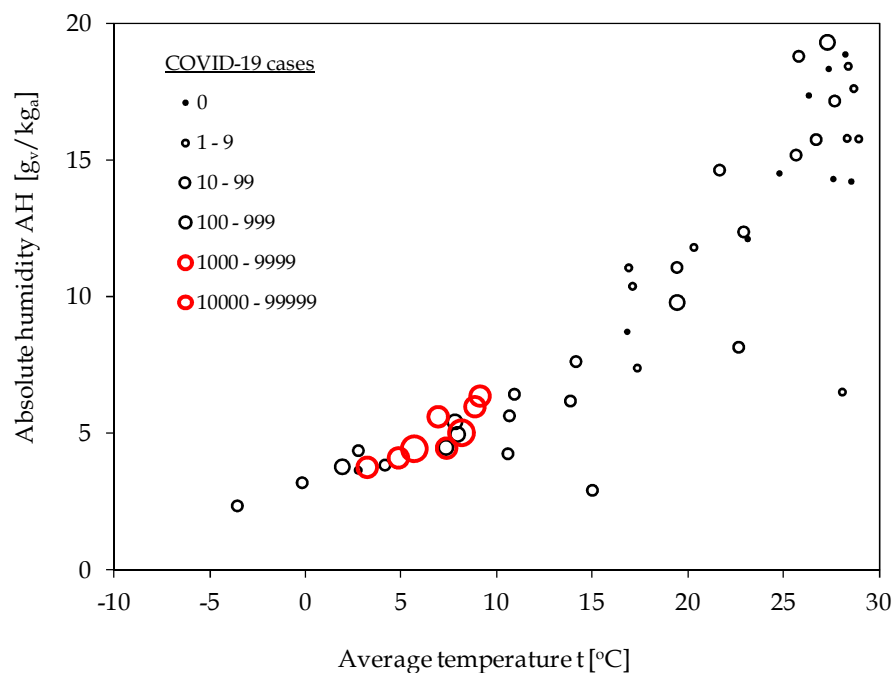


Fig 1. Infectivity data extracted from the study by Sajadi et al. [25].

3. Results

The elaboration of Fig. 1 is shown in Fig. 2, in which the psychrometric chart is superimposed on the distribution of the normalized data in order to show the related values of h and the RH% of moist air. These values were expressed as air temperature, t , in degrees centigrade and its AH in kgv/kg dry air, which is also called the humidity ratio and defined as the ratio of the mass of water vapor to the mass of dry air in the moist air sample, and calculated as follows:

$$h = c_a t + AH (c_v t + r) \quad (1)$$

$$(RH\%/100) = [p/p_s(t)] \times [AH/(AH+0.623)] \quad (2)$$

where c_a and c_v are the specific heats at the constant pressure of dry air and water vapor, which, around ambient temperature, can be assumed as equal to 1.006 kJ/kg °C and 1.86 kJ/kg °C, respectively; r is the latent heat of vaporization of water at its triple point equal to 2501 kJ/kg; p is the total pressure of the moist air, typically the barometric pressure related to the altitude above sea level in Pascal; and $p_s(t)$ is the saturated vapor pressure of water at temperature t in Pascal. The saturated water vapor pressure in Pascal can be calculated from the empirical formula derived by Hyland and Wexler for the temperature range of 0 to 200 °C [23, 26, 27]:

$$\ln[p_s(T)] = C_1/T + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 \ln T \quad (3)$$

in which $C_1 = -5.8002206 \times 10^3$, $C_2 = 1.3914493 \times 10^0$, $C_3 = -4.8640239 \times 10^{-2}$, $C_4 = 4.1764768 \times 10^{-5}$, $C_5 = -1.4452093 \times 10^{-8}$, $C_6 = 6.5459673 \times 10^0$, and T is the absolute temperature in Kelvin degrees: $T = t + 273.15$. If the RH% is known instead of the AH, the AH value in equation (1) to obtain the h value can be directly derived from equation (2) as follows:

$$AH = 0.623 [(RH\%/100) p_s(t)] / [p - (RH\%/100) p_s(t)] \quad (4)$$

Notice that the sizes of the circles were generally changed owing to normalization with respect to the total population of each city included in the analysis. Moreover, a number of circles were replaced by crosses when the percentage of the COVID-19 incidence fell below $5 \times 10^{-4}\%$, which appeared to be almost negligible. However, the comparison between Figs. 1 and 2 illustrates that most of the cities with the largest absolute numbers of infected people also shared the largest percentages of pandemic spread in the population.

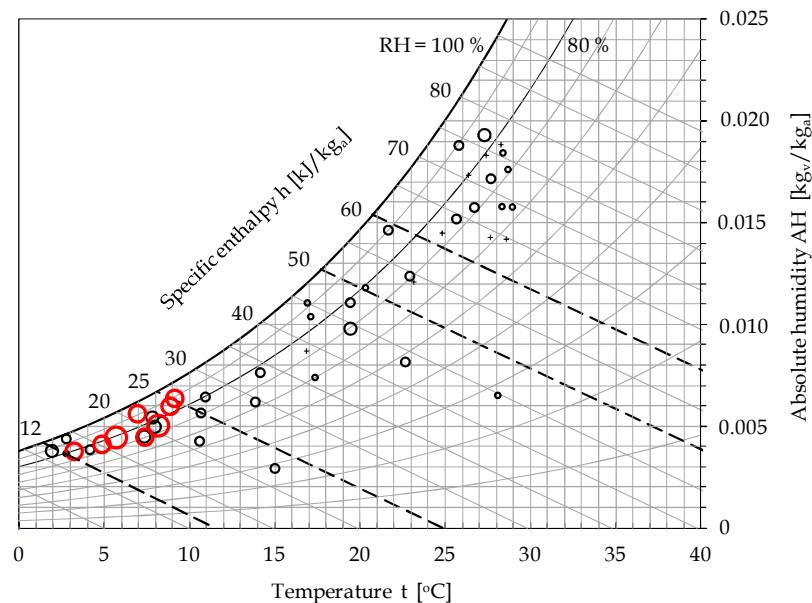


Figure 2. Elaboration of the data extracted from the study by Sajadi et al. [25]

As far as the h value is concerned, it is apparent that the climatic conditions related to the largest incidence of COVID-19 are such that the average specific enthalpies span the range of 12–25 kJ/kg dry air, which can be identified as the interval of the average h value corresponding to environmental conditions favorable to an increase in SARS-CoV-2 infectivity as known at the outbreak of the pandemic (consistent with Sajadi et al. until March 10, 2020).

In contrast, the IR appears to have been practically negligible in cities whose average h value fell in the range of 50–60 kJ/kg dry air, which we recently identified as the environmental h interval with the lowest virus survival [9]. Coincidentally, the climatic conditions corresponding to this enthalpy interval are typical of springtime for a number of cities that suffered from a large COVID-19 spread in wintertime.

The relationship between h and the IR recorded in any of the cities with significant community transmission of the pandemic is shown in Fig. 3. In order to identify the lower limit of the h range of atmospheric air corresponding to non-negligible spreads of COVID-19, we included the city of Moscow, which has one of the highest specific enthalpies among the densely populated cold cities that, according to Sajadi et al. [25], recorded a negligible IR on March 10, 2020. Since the weather data were available from airport weather stations rather than urban weather stations, a reasonable average 1.5 °C increase was applied to the temperature data before calculating h in order to account for the well-known urban heat island (UHI) effect, as well as the notion that in winter the UHI effect is generally less pronounced than in summer [28 - 30]. In the same figure, a cubic interpolation curve with an R^2 value of 0.643 ($p < 0.001$) is also displayed.

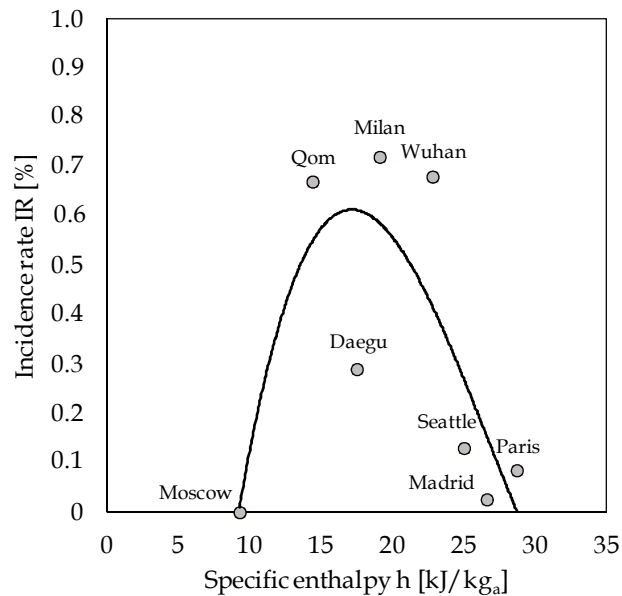


Figure 3. Interpolation curve incidence rate (IR) vs. specific enthalpy (h) for the seven considered cities with the addition of Moscow (data extracted from the study by Sajadi et al. [25]).

Although such a level of correlation could be considered satisfactory in the field of epidemiology, the limited data upon which the correlation is based cannot lead to the conclusion that the obtained result is sufficiently robust to be used for safe predictions. Moreover, it must be noted that the eight cities shown in Fig. 3 are not homogeneous at all in terms of social habits, urban texture, average age of the population, and availability of data. Therefore a new wider data analysis was performed, using a procedure similar to the one described above, by calculating the IR in the first 40 days after the first reported case in 30 Italian provinces, excluding the city of Milan, which was already included in the study carried out by Sajadi et al. For any province, the h value was more accurately evaluated by considering the time evolutions of air temperature and AH during the 20–30 days prior to the first reported case [31], again introducing the temperature correction mentioned earlier to account for the UHI effect. Thus, instead of using the 10-day average values of temperature and humidity to calculate the average h , the 10-day average h of the atmospheric air was obtained as the median of the ten daily average h values, each determined by replacing the daily average temperature and AH in equation (1). The results are listed in Table 1. In reality, the proposed set of Italian provinces, which can be considered as a representative sample of the whole country since approximately 42% of the Italian people live there, is undoubtedly much more homogeneous than the

set of cities considered by Sajadi and colleagues. Additionally, the climatic conditions of Italy span from those typical of the high-altitude mountains of Northern Italy (up to 46.5°N latitude) to those of the Mediterranean coastal areas (down to 36.5°N latitude), which means that nearly the whole range of h values under investigation is accounted for.

Table 1. Data from the 30 selected Italian provinces.

Provinces	Population	Cases after 40 days	IR (%)	h [kJ]/kg dry-air]
Bergamo	1114590	9712	0.87	18.9
Piacenza	287152	2892	1.01	19.6
Palermo	1252588	299	0.02	37.6
Cremona	358955	4233	1.18	15.9
Torino	2256523	5985	0.27	20.6
Roma	4342212	2714	0.06	32.0
Cagliari	431038	191	0.04	33.3
Pesaro - Urbino	358886	1919	0.53	23.2
Bari	1251994	886	0.07	27.0
Potenza	364960	162	0.04	28.3
Brescia	1265954	9477	0.75	21.8
Napoli	3084890	1643	0.05	29.3
Trento	541098	3053	0.56	11.8
Parma	451631	2083	0.46	25.9
Reggio Calabria	548009	276	0.05	28.1
Alessandria	421284	2248	0.53	23.6
Lodi	230198	2255	0.98	20.2
Verona	962497	3049	0.32	25.0
Bolzano	531178	1644	0.31	11.5
Aosta	125666	993	0.79	16.0
Trieste	234493	821	0.35	24.8
Teramo	308052	511	0.17	26.4
Genova	841180	2918	0.35	30.6
Perugia	656382	950	0.14	26.2
Firenze	1011349	1715	0.17	32.2
Brindisi	392975	428	0.11	28.6
L'Aquila	299031	220	0.07	9.6
Savona	276064	654	0.24	27.8
Campobasso	221238	191	0.09	9.6
Latina	575254	419	0.07	26.2

We performed a curve fitting analysis to find the best adaptation to our data. The relationship between the IR and the average h recorded during the 10-day observation period in the 30 selected Italian provinces is shown in Fig. 4. The best-fit interpolation equation is presented as follows:

$$\text{IR (\%)} = 1.093 \times 10^{18} / [h^{10.93}(e^{177/h} - 1)] - 0.15 \quad (5)$$

The observed R^2 value of 0.798 ($p < 0.001$) is generally considered strong in the field of biology. This reasonably enables us to state that up to nearly 80% of the variability in IRs (cumulative new cases per province population) was explained by h values at the beginning of the pandemic. We can also note that although other variables are certainly relevant in the determinism and dynamics of the epidemic, the h value seems to play a major role, especially when its value ranges between 12 and 23 kJ/kg dry air. This range corresponds to IRs $> 0.5\%$, which is just below 50% of the peak rate (approximately 1.05%). The shape of the curve confirms that the spread of COVID-19 started from climatic conditions having h values of atmospheric air spanning in the approximate range of 9–33 kJ/kg dry air. Correspondingly, h values in the range of approximately 0.03–0.3 kJ/kg of water vapor together with AH in the interval from 3–9 g/kg dry air occurred in the selected provinces. The above conditions can be easily summarized by the assessment of a wet bulb temperature from nearly

0–12°C with a critical value around 4°C, which is in particularly good agreement with the results from the study by Sahin et al. [15].

The asymmetry of the curve, even if weak, appears significant in itself. While extinguishing slowly at the higher values of h , which seems to be complementary with our cited findings regarding significantly shorter coronavirus survival in the range of 50–60 kJ/kg dry air [9], the suddenly sinking shape at the lower values of h clearly confirms that however high the RH value, the seasonal virulence of SARS-CoV-2 expires upon approaching 0°C.

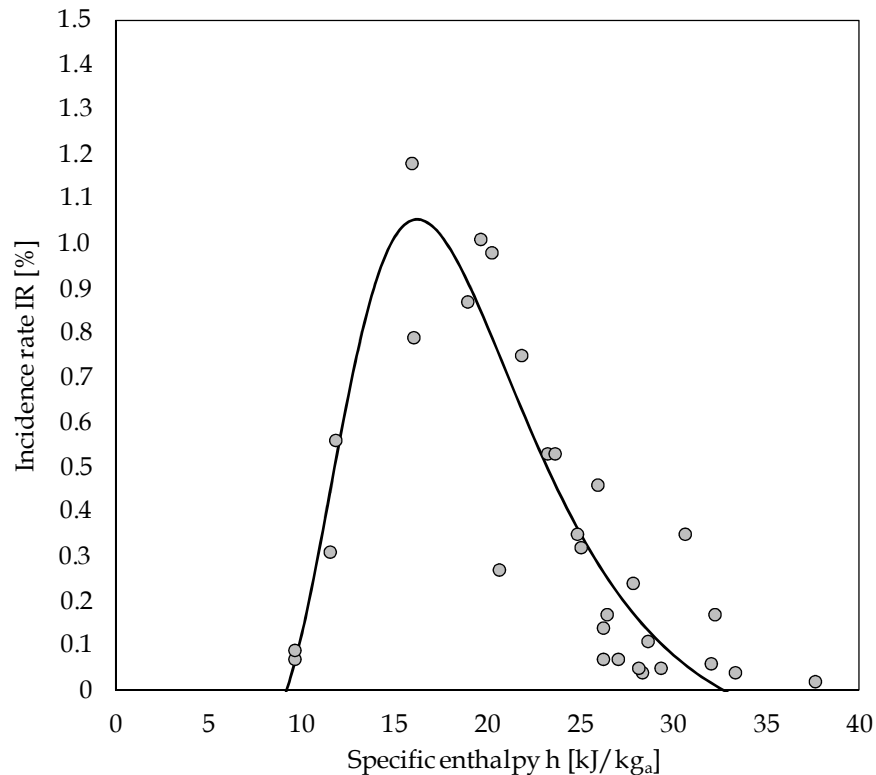


Fig 4. Interpolation curve incidence rate (IR) vs. specific enthalpy (h) for the 30 Italian provinces listed in Table 1.

3.1 Proposal of an enthalpy-based risk scale

Apart from more specific considerations and regardless of the IR sampling time, a correlation between infectivity and both temperature and humidity of the outdoor environment appears to exist, allowing us to unlock the acknowledged methodological impasse that has continuously inhibited researchers from obtaining conclusive results. This enables us to propose an h -related risk scale for evaluating the danger of COVID-19 spread as a potential consequence of the persistence of weather conditions favorable for SARS-CoV-2, which is expressed in terms of seasonal virulence risk (SVR) as defined in Table 2.

Table 2. Proposed h-related risk scale.

Specific enthalpy (h) range	Level of seasonal virulence risk (SVR)
$h < 9 \text{ kJ/kg}$	Negligible
$9 \text{ kJ/kg} \leq h < 12 \text{ kJ/kg}$	Low-to-average
$12 \text{ kJ/kg} \leq h \leq 23 \text{ kJ/kg}$	Average-to-high
$23 \text{ kJ/kg} < h \leq 33 \text{ kJ/kg}$	Low-to-average
$h > 33 \text{ kJ/kg}$	Negligible

In order to yield an easy-to-use tool, a chart expanding the obtained h values in terms of coupled temperatures and RHs of the atmospheric air is depicted in Fig. 5, where the corresponding levels of SVR are also marked. The dashed lines denote fields where the data rarely occur. It can be recognized that safer climatic and geographic conditions occur with higher RH at the highest temperatures and lower RH at the lowest temperatures. The latter statement is in good agreement with nearly all past observations in the literature [32-35], thus overcoming their apparent contradictions.

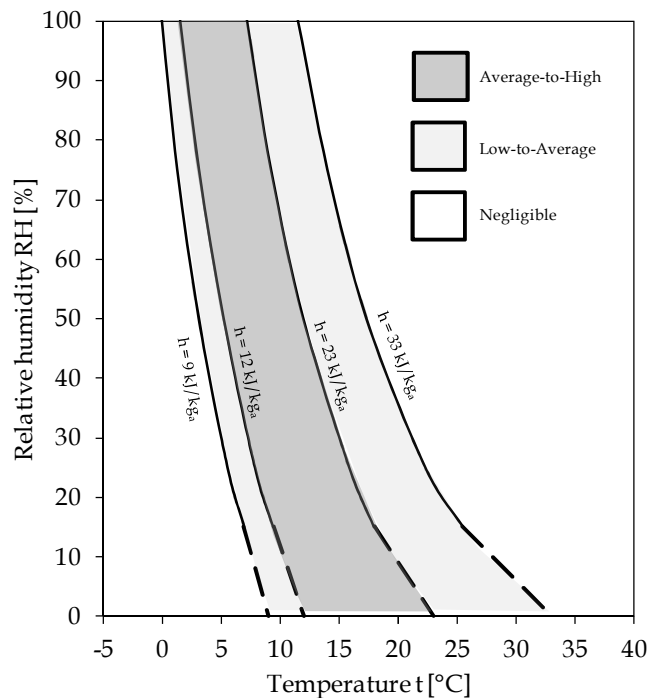


Fig 5. A chart of the suggested levels of seasonal virulence risk (SVR), expressed in terms of relative humidity (RH) and temperature of the atmospheric air.

The proposed risk scale has been subjected to the following verifications. First, we examined the transmissions of COVID-19 in the eight cities mentioned in Fig. 3, whose actual IR values and the related levels of risk have been compared with the SVR levels predicted according to the average h value in the 20–30 days prior to the recording of the first death or infection. The results are displayed in Fig. 6, in which the data related to London and New York, whose IR percentages are 0.30 and 0.94, respectively, were also added for further comparison. It is apparent that aside from the city of Daegu, the predicted enthalpy-based level of risk appears to be in considerably good agreement with the available infectivity data.

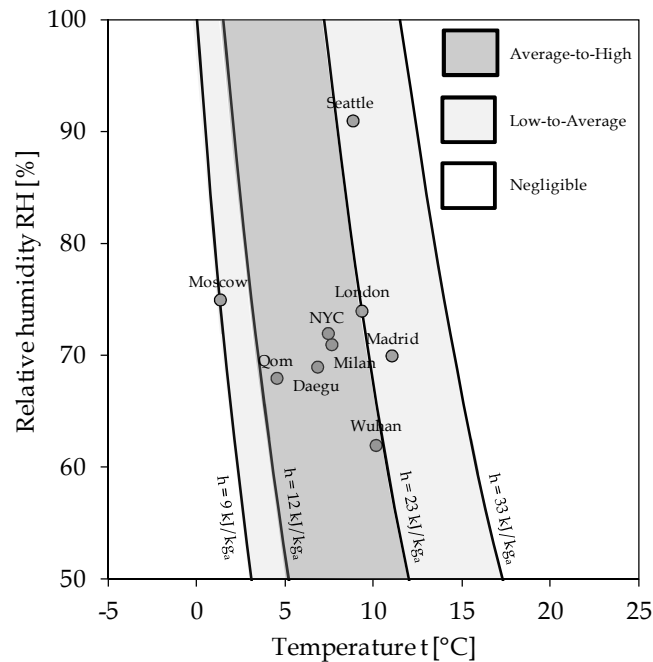


Fig 6. Verification of the cluster of ten global cities over the proposed chart of seasonal virulence risk (SVR) levels.

As a second check, the proposed 12-23 kJ/kg dry air range of h values corresponding to an average-to-high level of risk fits well with the results recently achieved by Ficetola and Rubolini [36], who assessed the effects of temperature and humidity on the global patterns of COVID-19 early outbreak dynamics from January–March 2020 throughout 121 countries around the world. In reality, the monthly average specific enthalpies of atmospheric air, calculated using the average temperature and AH data extracted from the WorldClim 2.1 raster layers [37] for the most severely hit countries included in their investigation, always span between 15–20 kJ/kg dry air.

As further verification, the proposed scale resulted in good agreement with the results of the study by Ahmadi et al. [14], who investigated the effects of a number of climatic parameters on COVID-19 spread throughout several provinces in Iran from February 29–March 22, 2020. From their results, it can be ascertained a range of significant specific enthalpies roughly spanning from 11–28 kJ/kg dry air.

The above proposition is just an approximate method based on relatively limited data collected over various periods of time; however, within the limits of the adopted environmental approach, the predictions appear sufficiently well verified. This could motivate further developments that possibly consider other relevant environmental parameters.

4. Discussion

To end the debate on whether or not climatic conditions can play an independent role – and if so, to what extent – in COVID-19 onset and transmission [18, 38], a number of other factors must be considered [24, 39, 40] in scenarios of not only high complexity but also significant uncertainty, as mentioned at the beginning of this paper. The available number of cases, and especially deaths, in the total population are also influenced by the following factors: i) the number of investigations carried out, their statistical assessment, and possible under/overestimations [13, 41, 42]; ii) demography in terms of population age and density [43, 44]; iii) urban texture, mobility, and social habits of the population [45, 46]; iv) restrictions by local and national governments, such as quarantine and lockdown [34, 47]; and v) medical care and susceptibility of the hosts [48-50]. These factors are almost entirely unrelated to h . On this topic, the recent literature [51] has suggested that confounding factors, including some climatic ones [52, 56], are nearly ready to be satisfactorily weighed.

As discussed earlier, in order to mitigate the effects of the social and behavioral non weather-induced aspects as confounding factors, we restricted the collected data as far as possible to the first signs of the pandemic, namely the period from late January to mid-March. Moreover, to test the robustness of our estimations we qualitatively explored the time

preceding the outbreak of the pandemic. During the time when COVID-19 had not officially affected the populations and before stringent containment measures were implemented, the monthly statistical average h values from late 2019 to the beginning of 2020 in three of the most affected global cities are reported in Fig. 7, where the symbols denote the first recorded COVID-19 victim. It can be seen that the onset of the pandemic always followed a pronounced persistence into the average-to-high level of risk enthalpy area.

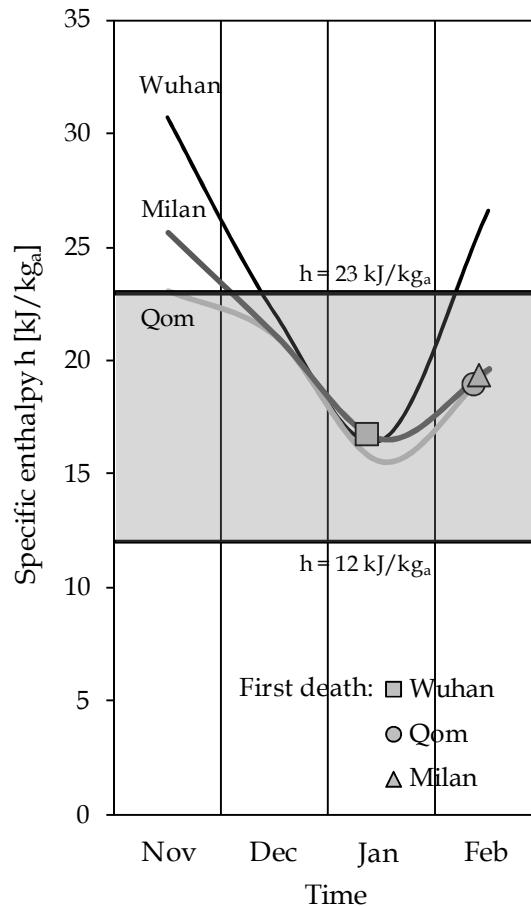


Fig 7. Time evolution of the monthly average specific enthalpy (h) statistical values from November 2019 to the time of the first coronavirus disease 2019-related death in the most adversely affected cities.

5. Conclusions

Even though further investigations could corroborate the robustness of the discussed method in relation to pollution (mainly PM) and radiation (as UV sunlight) effects, the presented data confirm a relationship between SARS-CoV-2 distribution patterns and the specific enthalpy h of atmospheric air, as noted in our previous paper. In fact, based on the analysis of the first 20–30 days of the epidemic in the selected Italian provinces with no influence from public health interventions, we were able to determine a correlating equation between the IR of COVID-19 and h , as well as propose an h -related seasonal virulence risk SVR scale to predict the areas with a potential danger of non-negligible SARS-CoV-2 spread due to favorable weather conditions. Accordingly, a chart yielding the SVR value of any possible coupled temperature and RH value is provided. In particular, sites with specific enthalpies of atmospheric air in the range between 9 and 33 kJ/kg dry air were classified as non-negligible risk areas even though the actual virus virulence was contingent on a

number of additional factors, such as social habits and mobility, the average age and density of the population, the reliability of statistics, the healthcare settings, and the promptness of the government to impose quarantine or lockdown measures.

The proposed risk scale was verified by examining COVID-19 transmission in a number of cities all around the world, which demonstrated good agreement with the available infectivity data. Furthermore, we showed that the pandemic onset generally occurred after an extended persistence into the environmental h range between 12 and 23 kJ/kg dry air, which was classified as average-to-high risk.

Our method overcomes the methodological impasse caused by the fact that temperature or humidity cannot be independently correlated with coronavirus viability, thus providing the scope for further investigation. And the results show that, based on limited statistical weather data from any site, one could predictively evaluate the season in which the corresponding h value falls in the domain of the ascertained starting preconditions for the possible onset and diffusion of COVID-19 and the period for which such a situation could occur.

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