International Journal of Environmental Science and Technology
https://doi.org/10.1007/s13762-020-02991-8

ORIGINAL PAPER

The role of temperature on the global spread of COVID-19 and urgent solutions

I. Roy[1]

Received: 22 June 2020 / Revised: 6 October 2020 / Accepted: 19 October 2020

Abstract

This study explored whether the global temperature had any role in the spread and vulnerability to COVID-19 and how that knowledge can be used to arrest the fast-spreading disease. It highlighted that for transmitting the virus, global temperature played an important role and a moderately cool environment was the most favourable state. The risk from the virus was reduced significantly for warm places and countries. Based on the temperature of March and April, various degrees of vulnerability were identified and countries were specified. The maximum reported case, as well as death, was noted when the temperature was in the range of around 275 °K (2 °C) to 290 °K (17 °C). Countries like the USA, UK, Italy and Spain belonged to this category. The vulnerability was moderate when the temperature was less than around 275 °K (2 °C), e.g. Russia, parts of Canada and a few Scandinavian countries. For temperature 300 °K (27 °C) and above, a significantly lesser degree of vulnerability was noted. Countries from South Asian Association for Regional Cooperation, South-East Asia, the African continent and Australia fell in that category. This work discussed that based on the variability of temperature, countries can switch from one vulnerability state to another. That influence of temperature on the virus and results of previous clinical trials with similar viruses provided a useful insight that regulating the level of temperature can offer remarkable results to arrest and stop the outbreak. Based on that knowledge, some urgent and simple solutions are proposed, which are practically without side effects and very cost-effective too.

Keywords Coronavirus · COVID-19 · Seasonality · Temperature · Urgent Solutions

Introduction

The recent pandemic of coronavirus disease 2019 (COVID-19) and its rapid spread worldwide (JHUM 2020; ECDC 2020a) brought the whole human civilization to a standstill. The responsible virus for the disease is severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (WHO 2020). Detailed analysis of the characteristics of the virus and the nature of the disease is outlined in current research (Gorbalenya et al. 2020; Chen and Li 2020).

The disease first originated in the Wuhan Province of China. The case of hospital admission was first reported on 12 December 2019, and since then, till 15 March there were 80,995 reported cases in China with 3203 confirmed deaths (ECDC 2020a). Various analyses on the COVID-19 spread in China were detailed in a recent study (Li et al. 2020). That figure all over the globe reached 1000,249 and 51,515, respectively (ECDC 2020a) on 3 April 2020, since 31 December 2019. Geographic distribution of COVID-19 cases worldwide during the initial phase of the outbreak is presented in Fig. 1. The disease being highly contagious in nature (WHO 2020; ECDC 2020b), most of the countries worldwide started lockdown situation from around the third week of March (Wikipedia 2020a) and continued the whole of April. This study mainly focused the initial period of the outbreak, till the beginning of May.

Several facts highlighted that the spread of recent coronavirus pandemic showed some geographic preferences (Fig. 1). Countries and cities with moderately cold winter temperature indicated a rapid spread (UK, Italy, Spain,

Editorial responsibility: Samareh Mirkia.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s13762-020-02991-8) contains supplementary material, which is available to authorized users.

I. Roy
indrani.roy@ucl.ac.uk

[1] University College London (UCL), IRDR, London, UK

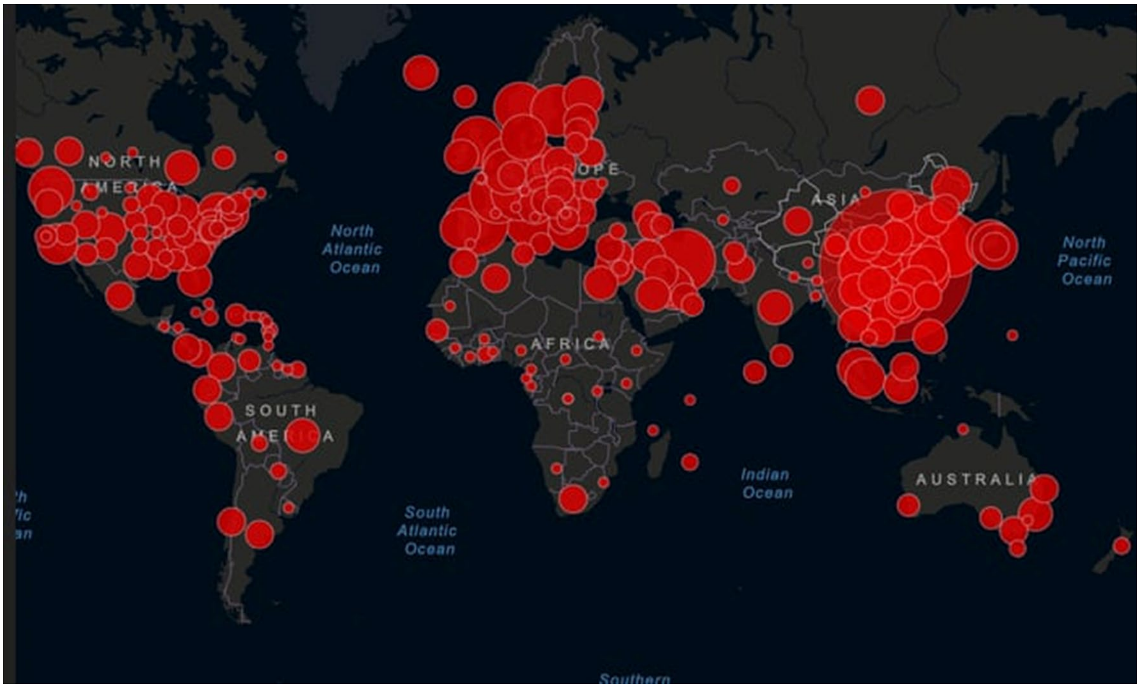

Fig. 1 Geographic distribution of COVID-19 reported cases worldwide, as of 16 March 2020, and the pattern is very similar till end of April (JHUM 2020)

northern USA, etc.) compared to warm countries (e.g. countries from the African continent, Indian subcontinent and Australia) (JHUM 2020; ECDC 2020a). Moreover, very cold countries like Canada, Russia and Scandinavian countries only showed moderate severity. Interestingly, the countries that suggested moderate severity started showing the sign of more severity from the end of April. More importantly, it is happening in spite of a global lockdown situation. Over the same time, some warm countries (e.g. Brazil, Chilli) also suggested a rise in severity (JHUM 2020; ECDC 2020a).

On a regional basis, compared to warmer places, colder regions were seen more affected. During February and January 2020, a sub-zero minimum temperature was noted in the Wuhan province of China where the outbreak was reported first. Wuhan experienced maximum severity in terms of the death toll and the rapid rise of infected patients. In February this year, the following cities (Rome in Italy, Tehran in Iran, Seoul in South Korea) all experienced a sub-zero minimum temperature and coincidentally showed a sharp increase in the number of infected patients. Those cities were the epicentres of the outbreak of respective countries. The numbers of infected people in Italy, Iran and South Korea are reported to be 115,242, 50,468 and 10,062, respectively (as of 3 April 2020 since 31 December 2019) (ECDC 2020a).

Close connections between epidemics and seasons are previously identified for mid-latitude temperate regions, which is November till March in the Northern Hemisphere, while it is May to September in the Southern Hemisphere (Lowen et al. 2007; Shaman and Kohn 2009; Lipsitch and Viboud 2009). In temperate regions, absolute humidity minimizes in winter alongside temperature which becomes more susceptible to certain virus transmission and survival (Shaman and Kohn 2009).

A laboratory study using a seasonally dependent endemic virus that has close resemblance with coronavirus also confirmed the dependence of temperature and humidity on the spread of disease (Lowen et al. 2007). It showed that at a temperature of 5 °C and relative humidity (RH) 35% to 50% and the infection rate was very high (75–100%). When the RH was still kept at 35%, but only temperature was increased to 30 °C the infection rate surprisingly reduced to zero (Lowen et al. 2007). As the infection rate was reduced to zero at temperature 30 °C and humidity 35%, that estimation may be useful for arresting spread of similar viruses and needs further exploration.

Another virus named the Middle East respiratory syndrome coronavirus (MERS-CoV) that share genetic similarity with COVID-19 was shown to remain active for a long time in low humidity and low temperature (Van Doremalen et al. 2013). Studies with a different SARS-CoV (severe acute respiratory syndrome coronavirus) also noted the same connection (Yuan et al. 2006; Casanova et al. 2010; Chan et al. 2011). MERS-CoV and SARS-CoV both belong to the coronavirus genus in the Coronaviridae family (Gorbalenya et al. 2020).

Research also studied strength and activity for a similar generic coronavirus (viz. SARS-CoV) using variable levels of temperature and humidity (Casanova et al. 2010). It found that inactivation of the virus was faster at all humidity level if the temperature was simply raised to 20 °C from 4 °C. Also, the inactivation was more rapid if the temperature was further increased to 40 °C from 20 °C, suggesting **the virus is extremely sensitive to high temperature**. SARS could, however, be active for at least five days in typical air-conditioned environments which has relative humidity 40–50% and room temperature 22–25 °C (Chan et al. 2011). Studies with various coronavirus generic categories other than MERS and SARS also confirmed that low temperature significantly contributes to the survival and transmission of the virus (Seung et al. 2007; Casanova et al. 2010).

COVID-19 is an extremely contagious disease (WHO 2020; ECDC 2020b) as it invaded almost all parts of the globe in less than two months (JHUM 2020; ECDC 2020a). The nature of its transmission under variable temperature conditions also needs attention. A laboratory experiment was conducted using guinea pigs to examine the contamination of a similar seasonal airborne virus (Lowen et al. 2007). It studied the effect of temperature on airborne transmission as well as contact transmission. Increasing the temperature prevented airborne transmission, but could not stop contact transmission. When guinea pigs were kept in separate cages for 1 week at a temperature of 30 °C, no infection took place among recipient guinea pigs. But to simulate contact transmission, if those were kept in the same cage, between 75% and 100% became infected. **They, however, found no role of humidity in these experiments**.

Though the knowledge of temperature sensitivity to the similar seasonal virus is recognized, whether any early warning systems can be proposed on various space and time scales is yet to be determined (Fuhrmann 2010). The role of weather on the spread of COVID-19 was also studied in various analyses. Research confirmed dependencies on temperature and humidity (Yuan et al. 2006; Casanova et al. 2010) and wind speed and surface pressure (Scafetta 2020) for the spread of virus. A systematic review to understand the effect of temperature on COVID-19 was also conducted (Paulo 2020). It collected numerous recent journal submissions (around 16 in number) and almost all of them indicated a strong dependence on temperature. There are potential that the knowledge of such analyses can be used for the benefit of human society in the current emergency situation. The role of global temperature on the transmission of COVID-19 worldwide was mentioned first by the author in a recent work (Roy 2020a). That knowledge was further elaborated in a subsequent study by presenting a global temperature spatial map and comparing with vulnerability worldwide (Roy 2020b). The current analysis is an extension work (Roy 2020c) to investigate that effect further. It also identifies countries those are more advantageous/disadvantageous states than others in various seasons.

It is an extremely contagious disease (WHO 2020; ECDC 2020b) and has very high epidemic potential. Scientists from different fields are working tirelessly to mitigate the crisis. Clinical trials and laboratory experiments are time-consuming. Lockdown and social distancing can be a temporary solution, as the economy and mental health also need attention. With those emergency situations in mind, some effective solutions were proposed on 17 March (Roy 2020a). These additional measures, apart from existing guidelines (WHO 2020; ECDC 2020b), can greatly benefit to overcome the crisis.

This article is based on the idea whether the variable global temperatures have any role in the transmission of virus globally and how that knowledge can be used to arrest the rapidly spreading disease.

Date and location of the research: The period considered is up to beginning of May with the main emphasis on the month of March and April. Data considered are from all over the globe.

Materials and methods

Global air temperature data were analysed from NCEP/NCAR Reanalysis product (Kalnay et al. 1996), a joint product from the National Center for Atmospheric Research (NCAR) and National Centers for Environmental Prediction (NCEP). The data are freely available from the Web (PSL 2020). It has a temporal coverage of monthly as well as daily values from 1948 January till recent dates. The long-term monthly mean of these data is available and derived for years 1981–2010. The spatial coverage extends all over the globe and has 17 vertical levels. In this analysis, only the lowest level near the surface is considered, which is 1000 mb. For air temperature, climatology (30 years average) is calculated, as well as some daily composites using compositing technique. The method of mean difference was used to analyse the result and to find differences between two sets of data. The level of statistical significance was derived using the Student's *t* test. Data related to COVID-19 are collected from freely available site (Worldometers 2020a).

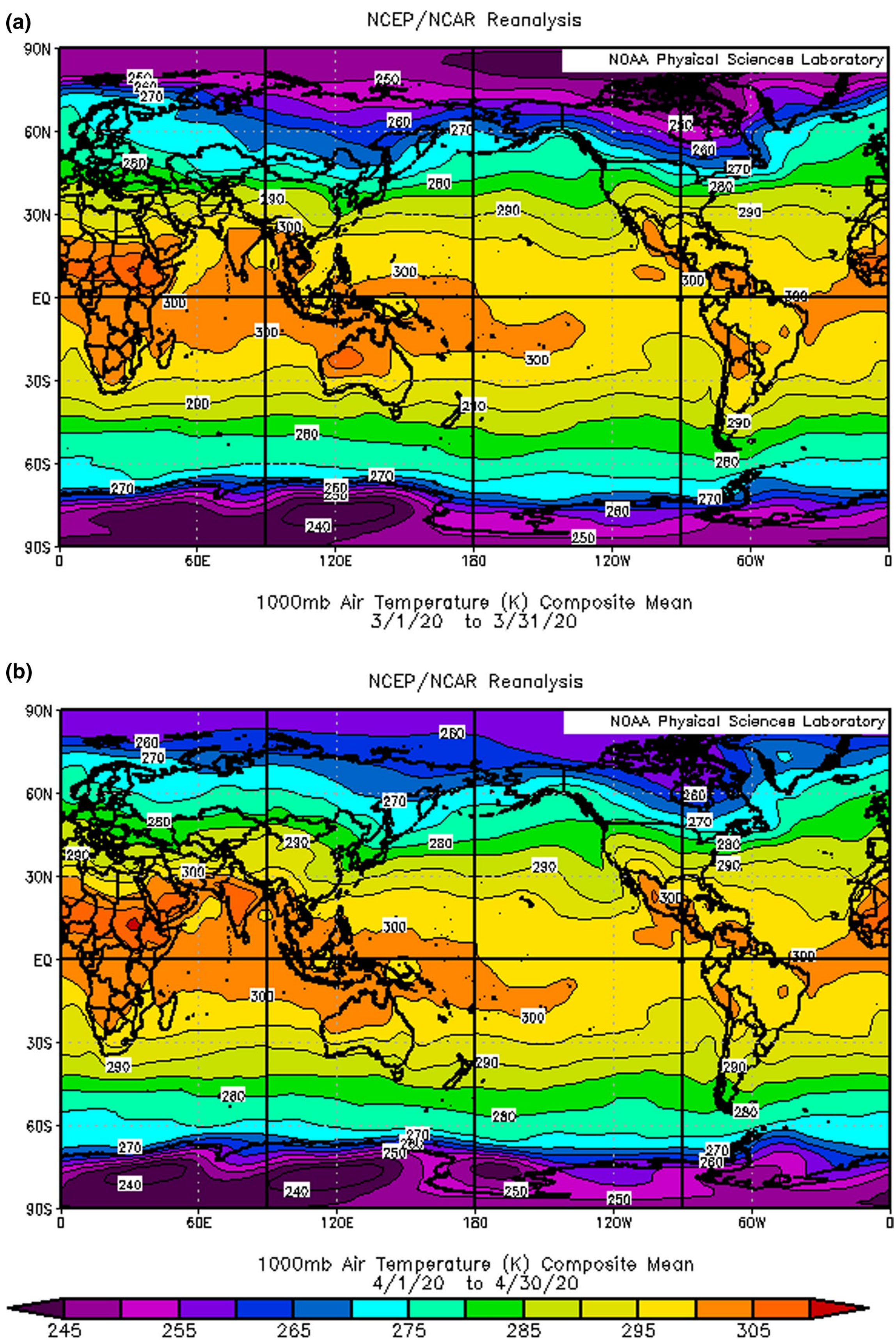

Fig. 2 Monthly average air temperature (°K) spatial plot globally for: **a** March 2020, **b** April and **c** February 15 till April 2020. Plots are generated from the NOAA/ESRL Physical Sciences Division, Boulder Colorado website at https://psl.noaa.gov/data/composites/day/

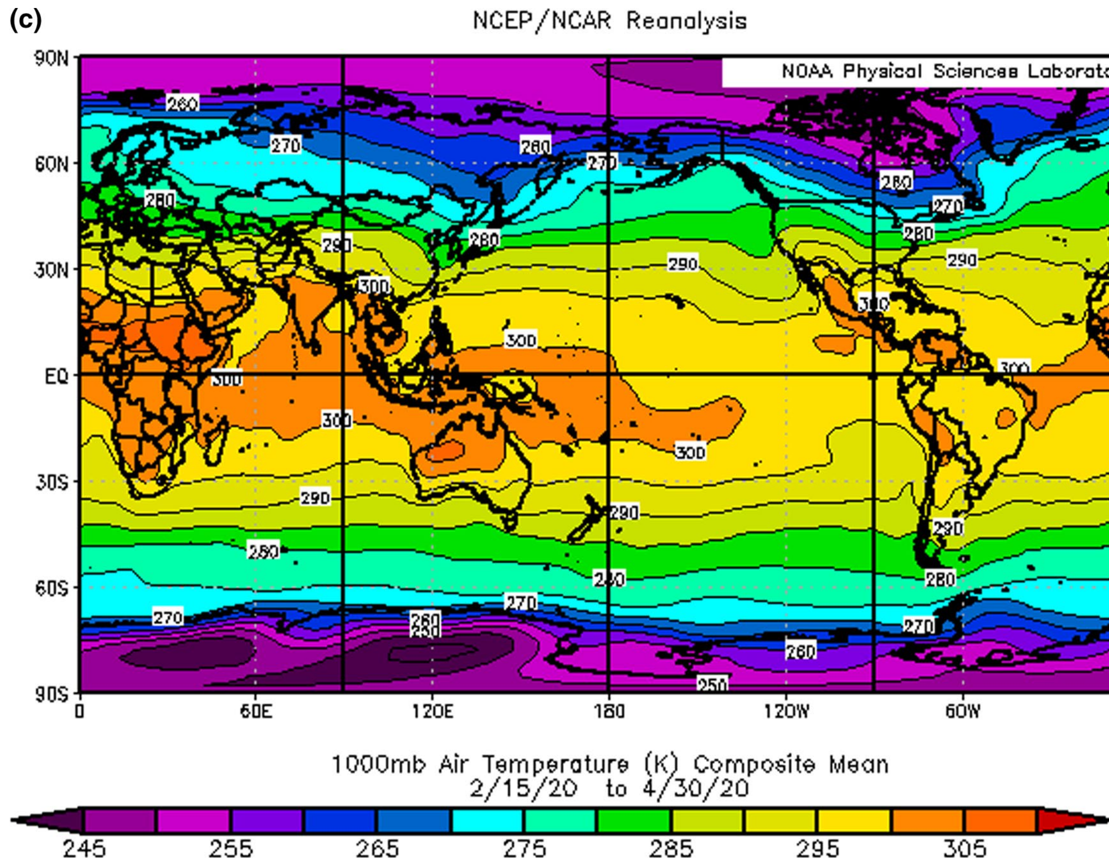

Fig. 2 (continued)

Results and discussion

Results

Analyses based on temperature and spread of the virus

As temperature played a very key role in spreading coronavirus (Seung et al. 2007; Yuan et al. 2006; Casanova et al. 2010; Chan et al. 2011; Van Doremalen et al. 2013) and also especially COVID-19 (Paulo 2020; Demongeot et al. 2020; Scafetta 2020), this study analysed it further by using a spatial plot of global monthly mean air temperature (Fig. 2). Later it was compared with the vulnerability to the disease worldwide.

Mean spatial temperature globally

Mean global temperature spatial plot for March 2020 is shown in Fig. 2a, when lockdown started (Wikipedia 2020a) and the disease affected most of the countries globally. Figure 2b is for the very recent month (April 2020) and Fig. 2c for the period when the disease made its presence globally (15 February) till the last day of recent month (30 April 2020).

Temperature threshold: Cold temperature

Different vulnerability situations were observed for moderate cold countries and extreme cold countries.

Moderate cold: The first ten countries (and number of death counts till 3 April) in descending order are mentioned: Italy (13,917), Spain (10,003), USA (6053), France (4503), China (3326), Iran (3160), UK (2921), the Netherlands (1339), Belgium (1011) and Germany (872) (ECDC 2020a). These countries showing maximum vulnerability belonged to the moderate cold category. Mean temperature varied between the range of around 275 °K (2 °C) and 290 °K (17 °C).

Severe cold: Though laboratory experiments, to our knowledge, did not conduct any study relating to lower temperature threshold, but Figs. 1 and 2a suggest, lower temperature threshold may also be important. Here are some statistics (ECDC 2020a) for reported case (and death) for countries below 275 °K (2 °C), e.g. Iceland 1319(4), Finland 1518(19) and Canada 11,268 (138); all those showed comparatively low death count till 3 April.

Temperature threshold: High temperature

Interestingly, countries having temperature more than 300 °K (27 °C) showed unusually low death rate compared to the overall statistics. Countries from the South Asian Association for Regional Cooperation (SAARC), southeast Asian countries (SEAC), the African continent and Australia all lied in that zone and all had low death counts (Figs. 1, 2a). African countries lying in that temperature zone reported insignificant infected cases as well as deaths. That temperature zone excluded countries with higher reported case among African continent (countries of northern boundaries, e.g. Algeria, Egypt and Morocco and Southern boundaries, e.g. South Africa). For Australia, that statistics of the reported cases (and deaths) were 5224 (23); in fact, no death was reported till 3 April (JHUM 2020) in regions when the temperature is higher than 300 °K (27 °C). Almost all reported cases and deaths for Australia were around south-east part of the country where the temperature was below 300 °K (27 °C) (Figs. 1 and 2a). Few other countries falling in that temperature threshold with reported cases (and deaths) were Malaysia 3116 (50), Singapore 1049(5) and Thailand 1875 (15).

Certain clinical tests found the infection rate for some seasonal airborne virus was reduced to zero at temperature 30 °C at certain humidity level (Lowen et al. 2007). Here, it is shown that the vulnerability to COVID-19 is reduced drastically even at 27 °C, without considering any effect of humidity. In addition to that, when the temperature was above 305 °K (32 °C), an unusually low number of the reported cases, as well as deaths, was observed (JHUM 2020). Global temperature did not reach more than 310 °K during April. When it is above 310 °K, people use more air conditioning in that uncomfortable state. That could be a likely cause of the rise in the transmission of disease at the later period of summer months in some countries. However, as this study only focused till the beginning of May, it is beyond the scope of discussion here.

These analyses indicated some rough temperature threshold for the spread and vulnerability to COVID-19 as follows: (i) 275 °K (2 °C) to 290 °K (17 °C)—maximum reported case as well as death; (ii) < 275 °K (2 °C)—death reporting was low; (iii) 300 °K (27 °C) and above—significantly less number of reported death compared to overall population; and (iv) > 305 °K (32 °C)—an unusually low number of reported cases as well as deaths.

Figure 2b shows the spatial plot of global temperature for April which is tested again, and the main conclusion relating to temperature threshold and vulnerability remains the same. Climatology of temperature is prepared globally for different months (Figs. 3, 4, 5, 6, 7, 8). Following the current analyses, it would indicate predictive maps of vulnerability for different months based only on temperature. Figure 2b is seen consistent with Fig. 3 (bottom) and Fig. 2c with Fig. 3 (top), which are for the month of February and March, respectively. As it verified the last February and March 2020 with the climatology of those two months, people can expect the predictive maps would be very similar for other months too. Thus, climatology map of temperature can give ideas of vulnerability level to different countries month-wise and the direction of transitions. It will be important for every country for future preparedness.

The vulnerability to the disease worldwide was analysed based on certain data on the day of 1 May. To examine those data till the 1 May (Table 1), global temperature map from 15 February till the end of April (Fig. 2c) was compared. The result was again found consistent.

Examining reported cases and deaths

Based on location, testing and other various reasons reported cases are likely to vary. As death reporting is usually authentic, this study considered 'deaths' as a better metric. Moreover, the absolute number of deaths varies based on population. Hence, to analyse the degree of vulnerability, death/million population of a country is chosen as the best indicator in this analysis.

Table 1 presents a few statistics showing situation update/performances of various chosen countries (Worldometers 2020a). Some countries, especially those are developing, could have poor reporting strategy and inadequate facilities. Tests/million population are expected to be comparatively low for those countries, as also reflected in Table 1 (last column). It should be noted that data or statistics presented in Table 1 could vary slightly and may not be accurate. However, those limitations do not affect the main results of the current analyses.

Test/million populations were maximum for Iceland, which was reflected in the highest number of infected cases per million (column 4). Death/infected (column 5) is a parameter that could indicate the performance of medical treatment country-wise and expected to be lower for developed countries. However, it is also linked with the number of more overage population and number of testing, etc. Death/infected (%) was highest in European countries in spite of advanced health care system, which may indicate a high ageing population. The same was the lowest for Singapore (.1%), which had high testing rates among all warm countries.

Data of all countries from South Asian Association for Regional Cooperation (SAARC) were presented which are Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka. All countries of southeast Asian region are also presented in Table 1. Those are Singapore, Cambodia, Malaysia, Vietnam, Thailand, Indonesia, Philippines and Myanmar. Among those, some are very popular tourist spots and some are popular international business

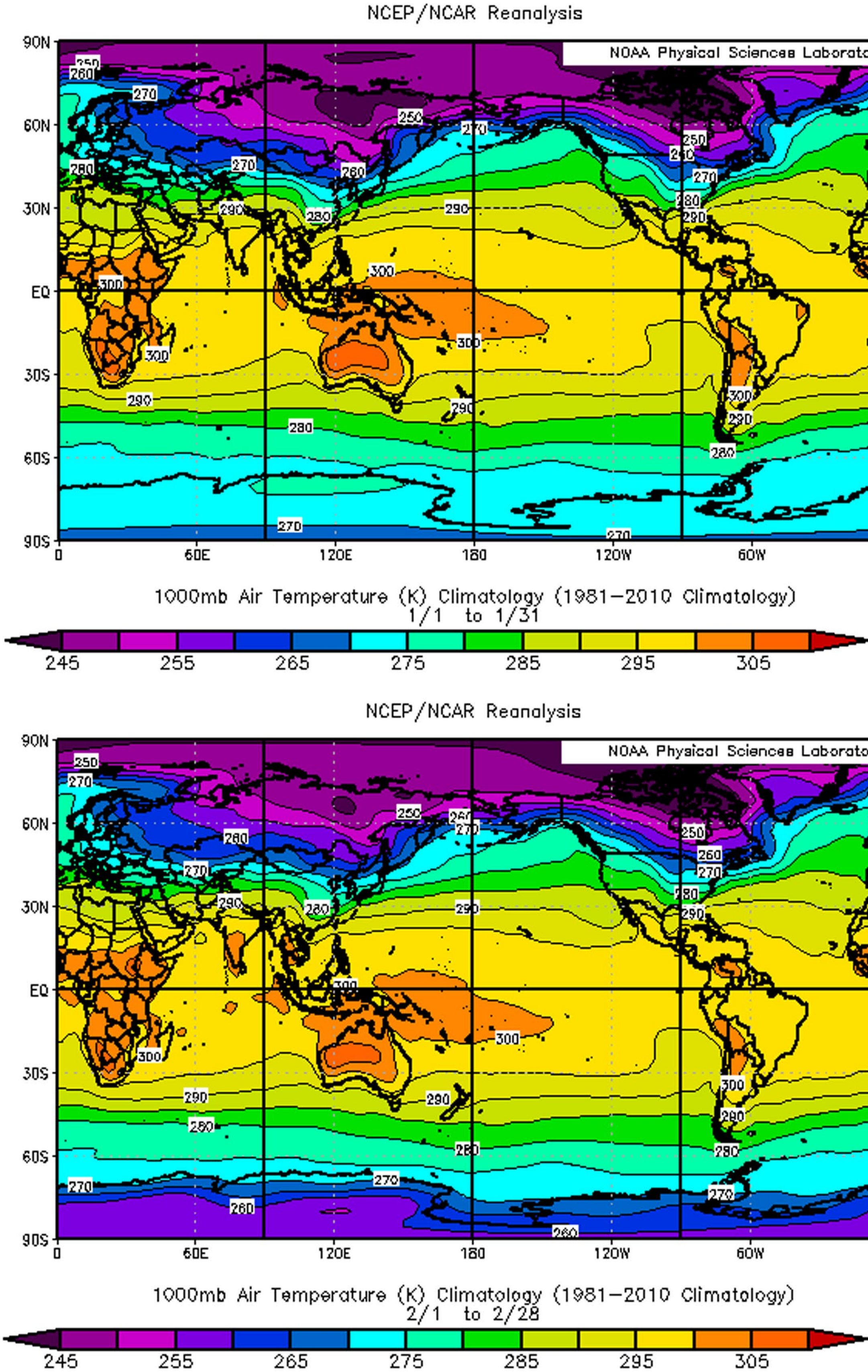

Fig. 3 Climatology of global temperature for January (top) and February (bottom)

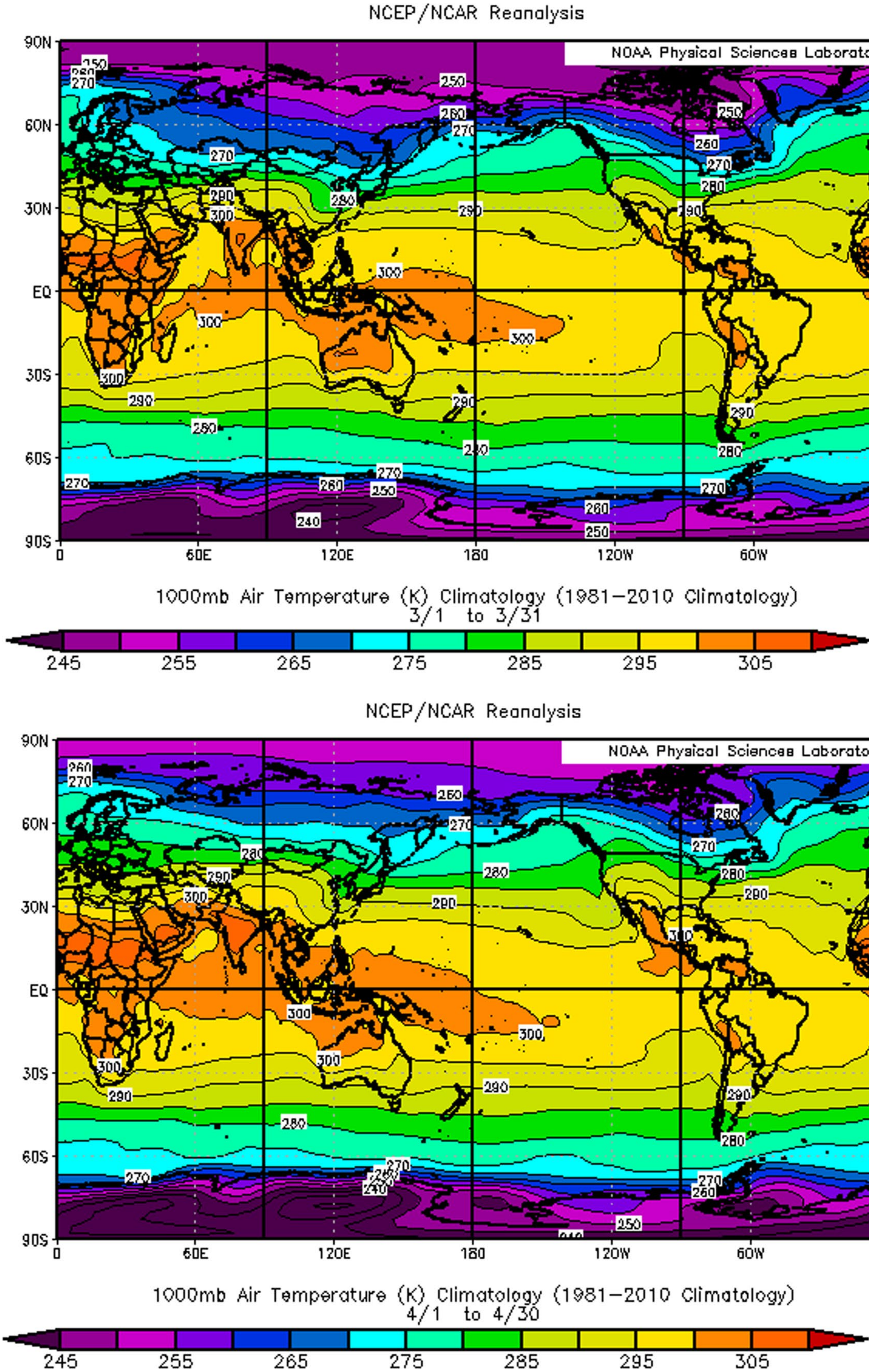

Fig. 4 Climatology of global temperature for March (top) and April (bottom)

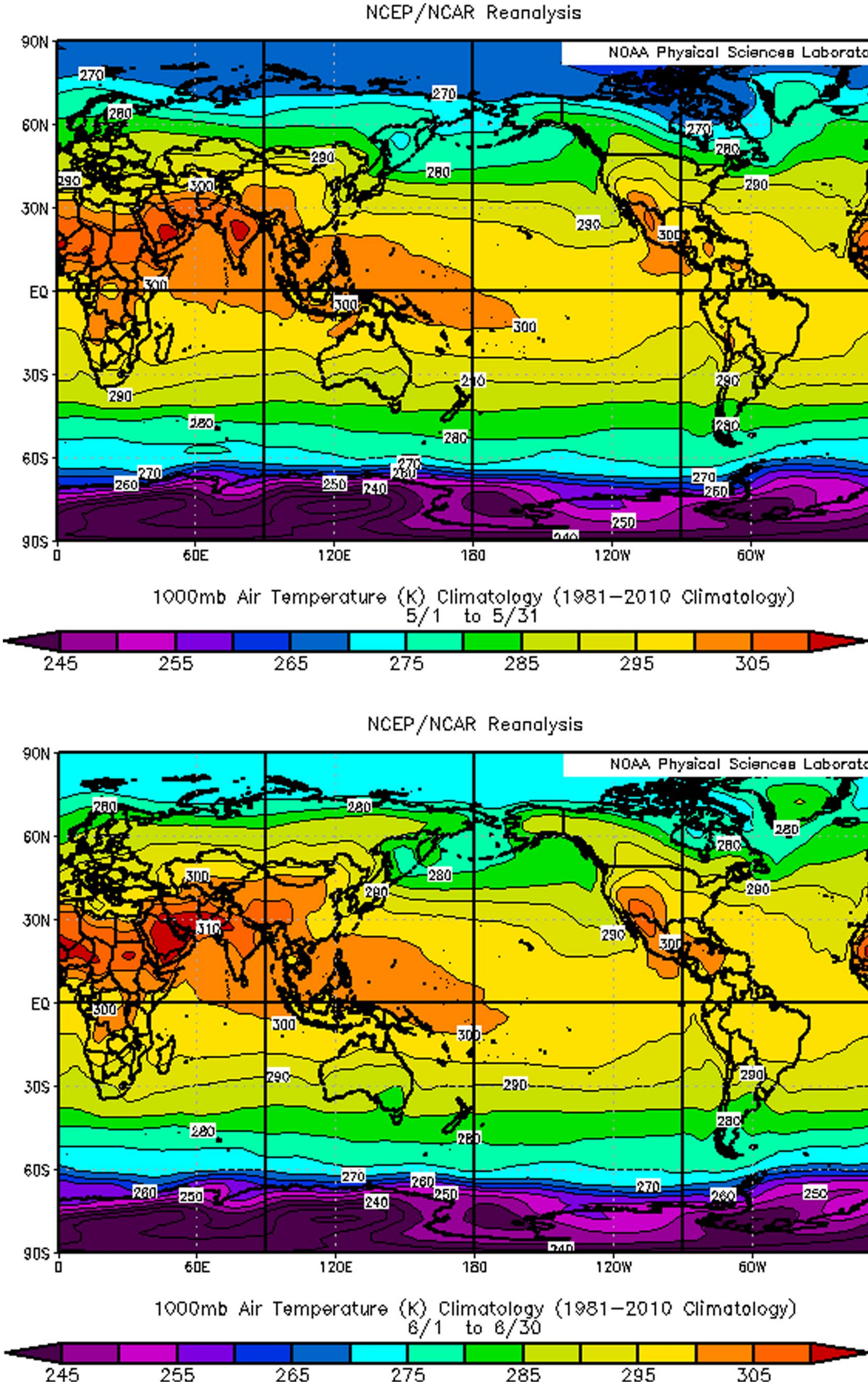

Fig. 5 Climatology of global temperature for May (top) and June (bottom)

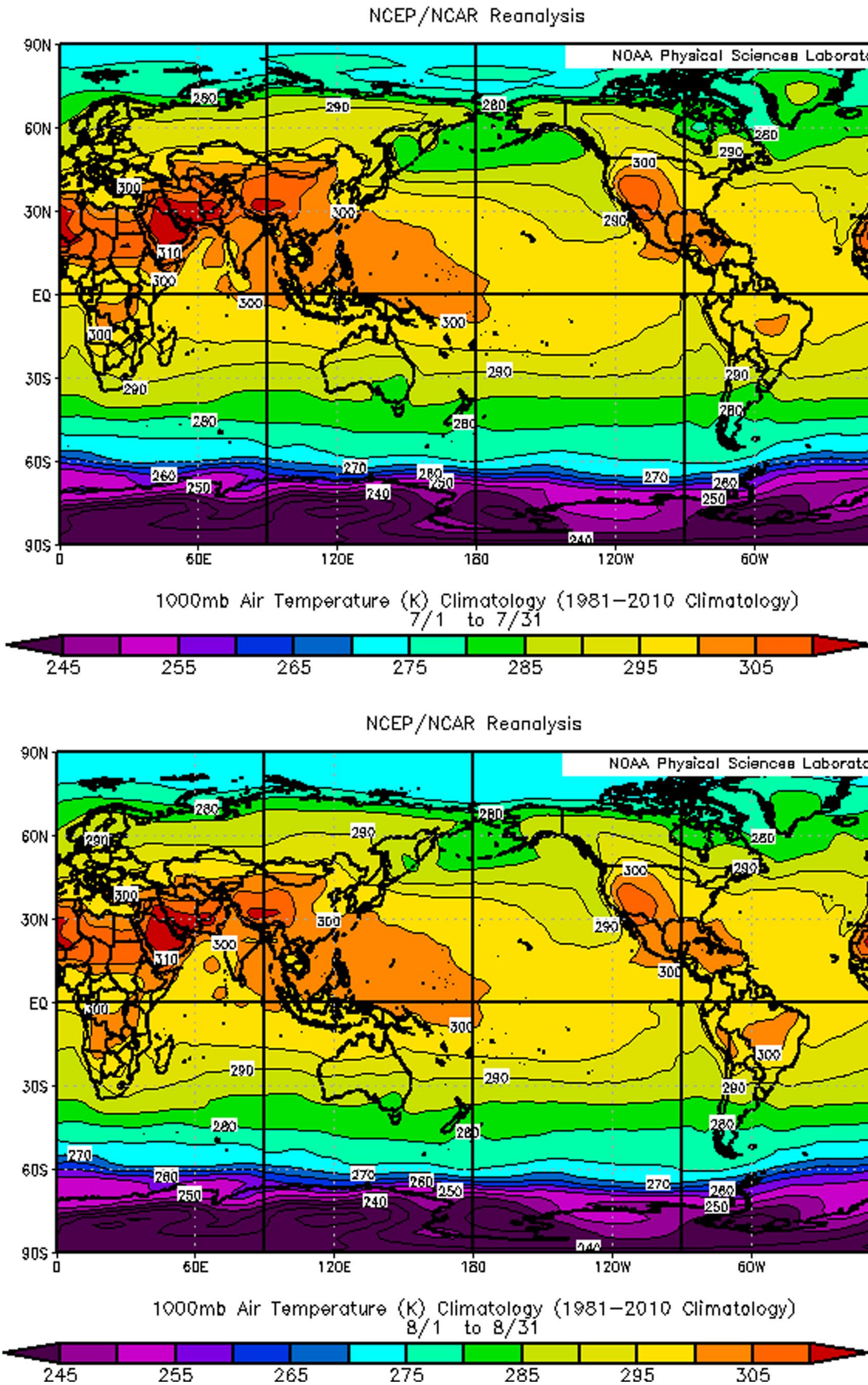

Fig. 6 Climatology of global temperature for July (top) and August (bottom)

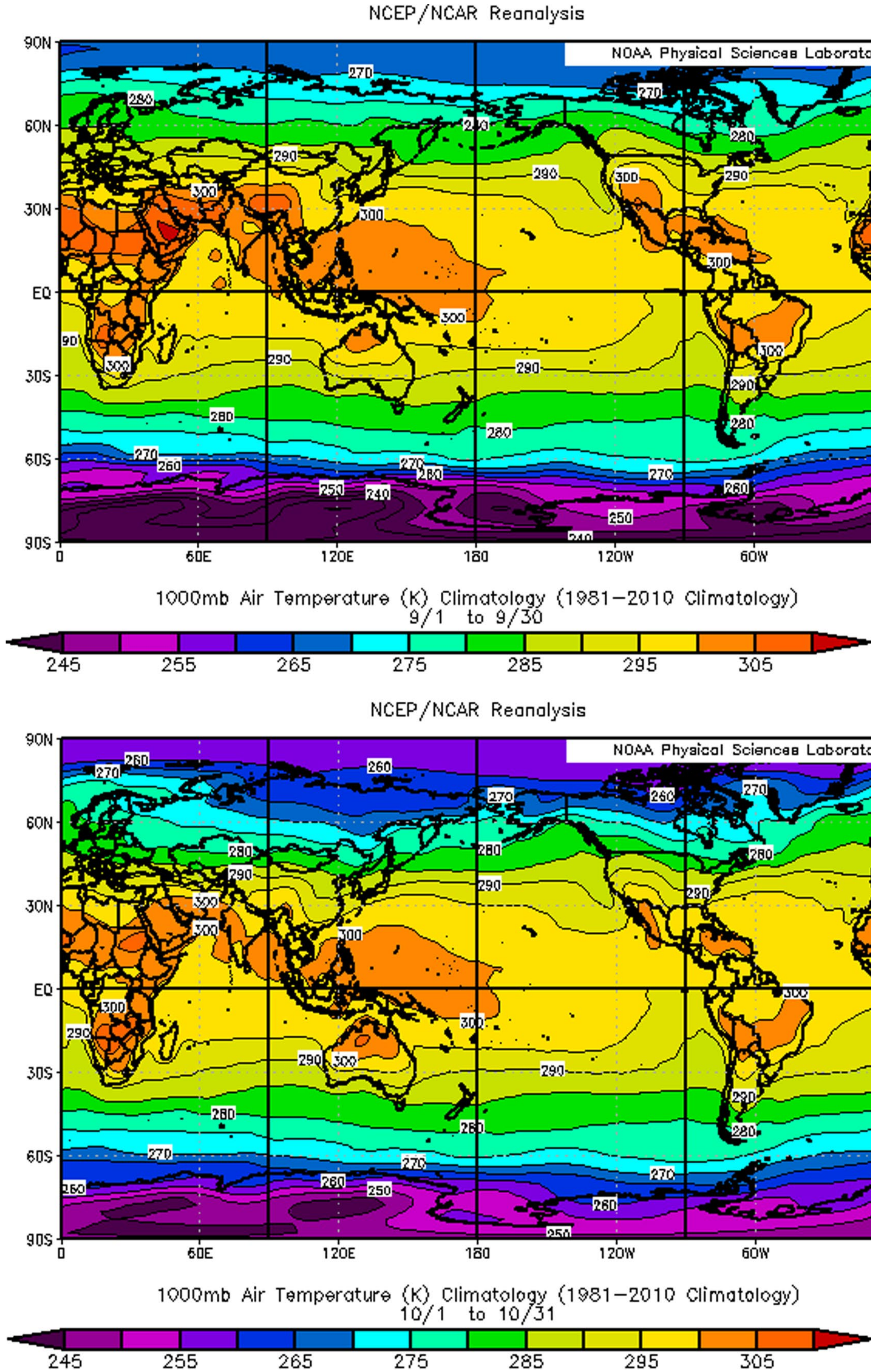

Fig. 7 Climatology of global temperature for September (top) and October (bottom)

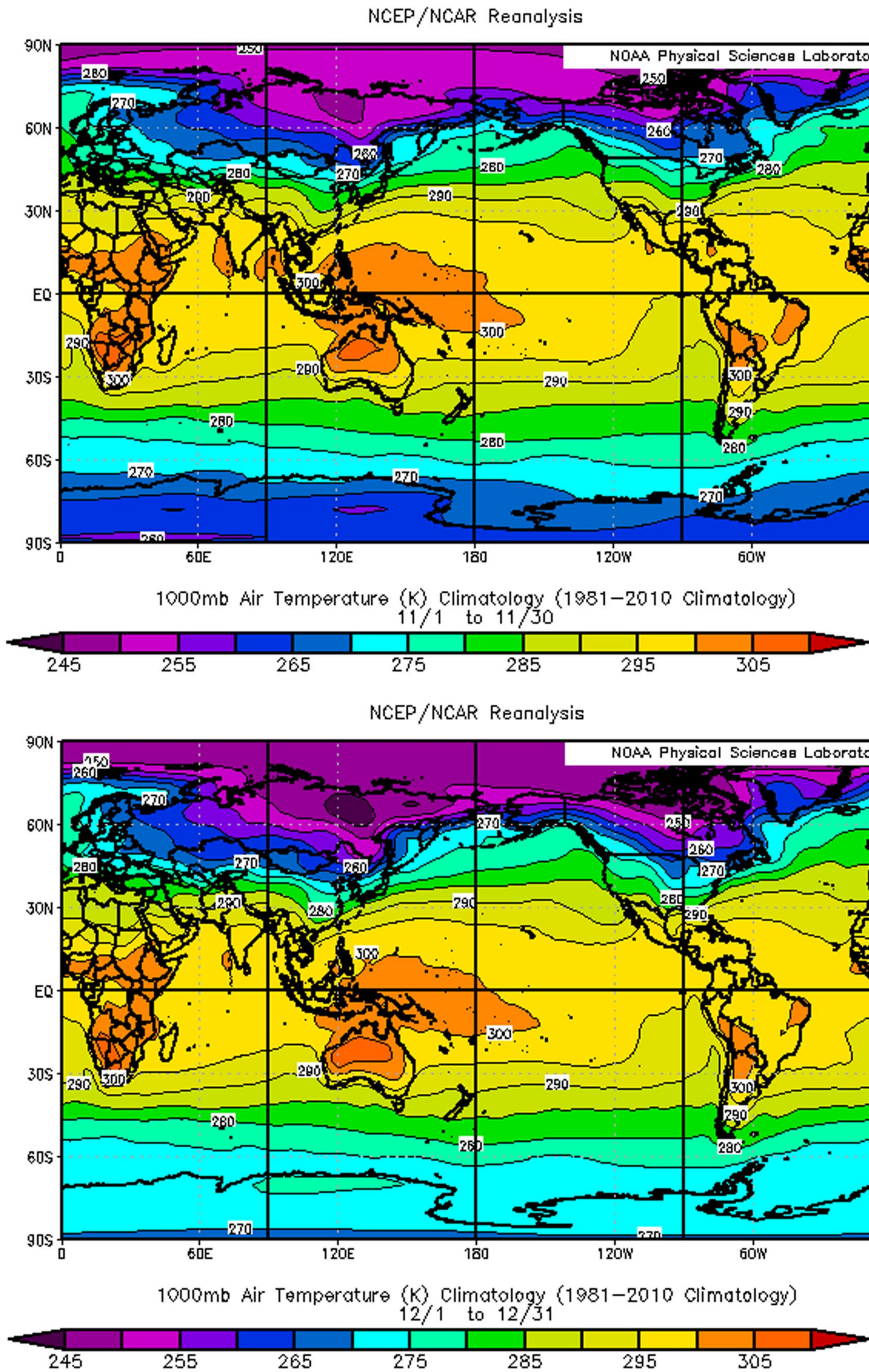

Fig. 8 Climatology of global temperature for November (top) and December (bottom)

Table 1 Reported cases and deaths of few countries as of 1/5/2020

Category	Countries	Deaths/million population	Infected/million population	Death/infected (%)	New deaths on the day 1/5/2020	Tests/million population
I	USA	199	3417	5.8	1897	20,241
Most vulnerable	*Europe*					
	Spain	531	5197	10.2	281	32,699
	Italy	467	3431	13.6	269	33,962
	UK	405	2614	15.5	739	15,082
	France	377	2564	14.7	218	16,856
II	Canada	90	1459	6.2	207	22,050
Moderately vulnerable	Russia	8	784	1.0	96	25,354
	Finland	39	912	4.3	7	17,615
	Iceland	29	5269	.55	0	143,988
III	*SAARC countries*					
Less vulnerable	India	.9	27	3.3	69	654
	Sri Lanka	.3	32	.93	0	1047
	Pakistan	2	82	2.43	56	825
	Afghanistan	2	60	3.3	4	272
	Bangladesh	1	50	2.0	2	426
	Bhutan	0	9	0	0	13,091
	Maldives	2	908	.22	0	14,815
	Nepal	0	206	0	0	2072
	Southeast Asian countries					
	Singapore	3	2923	.1	1	24,600
	Cambodia	6	138	4.34	21	2057
	Malaysia	3	188	1.59	1	5215
	Vietnam	0	3	0	0	2681
	Thailand	.8	42	1.9	0	2551
	Indonesia	3	39	7.7	8	374
	Philippines	5	80	6.2	11	992
	Myanmar	.1	3	3.3	0	152
	African Continent					
	Egypt	4	58	6.9	14	897
	South Africa	2	100	2.0	13	3668
	Algeria	10	95	10.5	3	148
	Morocco	5	124	4.03	1	1003
	Australia	4	265	1.5	1	23,093
IV	*African Continent (Central region)*					
Least vulnerable	Uganda	0	2	0		739
	CAR	0	15	0		
	Eritrea	0	11	0	Nil	
	Ethiopia	.03	1	3		181
	Chad	.3	4	7.5		

hubs where more transmission of the disease by foreign travellers are expected. In spite of the varied level of testing, infrastructural facility, population density, varying degree of lockdown restriction and many dissimilarities among each country, there was still one common factor. All those countries had very less death per million population. For SAARC countries, it was 2 and under, whereas for southeast Asian countries (SEAC) it was 6 and under. Among these countries, Singapore did maximum testing per million, which was even comparable with developed countries. That large count was reflected in the higher count for infected per million compared to other countries in that group, though not in the death count. Among that group of countries, the number of deaths in one day (01/05/2020) was higher in India and Pakistan compared to the rest (column 6), which was a common reflection of their high population.

Table 1 suggests that the least vulnerable countries had a very less count of death per million, which was under 1. That count for less vulnerable countries were 10 and under. Results of few moderate cold countries and very cold countries were also presented. For moderate cold countries, the deaths per million was very high which even exceed 400 in some countries. Though the USA ranked first in terms of total number of deaths and reported cases (JHUM 2020), but being third-largest populated countries in the world (Worldometers 2020b), the ranking of the USA in Table 1, column 3, was lower than in European countries. For very cold countries, that count was less than 100 for most cases.

Following temperature thresholds, countries were categorized based on vulnerability as follows:

Category I: Moderately cold—between 275 °K (2 °C) to 290 °K (17 °C)—most vulnerable.
Category II: Very cold—less than 275 °K (2 °C)—moderately vulnerable
Category III: Moderate warm—greater than 300 °K (27 °C)—less vulnerable.
Category IV: Very warm—greater than 305 °K (32 °C)—least vulnerable.

There could still be a very few countries suggesting as outliers. Those could be related to relaxed/effective social isolation policy and preventive measures, low/high testing facility, relaxed/regulated overseas arrivals, poor/advanced infrastructure, inadequate/appropriate medical intervention on time, other favourable/unfavourable atmospheric conditions, etc.

Statistical analyses

Figure 9 shows vulnerability to COVID-19 measured in terms of deaths per million, up to 1 May 2020. Figure 9a suggests all Warm countries together (SAARC and southeast Asian countries (SEAC), continents of Australia and Africa) had significantly low death rates compared to cold countries. Mean and standard deviation of moderately cold (395.8, 125.0), very cold (41.5, 34.8) and warm countries (2.1, 2.4) suggested a clear distinction. In the group of warm countries, there were enough dissimilarities among each other in various respects (varied testing level, popular tourist destination, infrastructural facility, other atmospheric conditions, developed/developing status of countries, etc.). The low mean and standard deviation clearly indicated how strong was the role played by temperature. The method of mean difference is applied among the three categories, and to test the level of statistical significance, 't' test was used. The difference between each other in the three categories was significant even at the 99% level. In Fig. 9b, it further elaborated on warm countries and presented box plots focusing on countries from SAARC and SEAC. Each group comprised of a total of 8 countries. The SAARC group of countries indicated the lower mean value (1.0) and standard deviation (.8) than the group of SEAC (2.6 and 2.2, respectively). Figure 9c further focuses each individual countries from Fig. 9b. Among SAARC countries, Pakistan, Afghanistan and Maldives showed highest rate, while from SEAC, countries with high death counts were Cambodia and Philippines. Figure S1 is same as Fig. 9 though considered reported cases per million instead of death. Countries with more number of testing sometimes report more cases (e.g. Singapore, Maldives and Iceland).That is one of the reasons for large standard deviations in Fig. S1a. Like death, there is a very clear distinction between three categories (Fig. S1a). In Fig. S1b, we excluded two outlier countries Singapore and Maldives those did very high testing compared to the rest. The box plot of SAARC and SEAC did not differ much. In Fig. S1c too, it excluded those two outliers for general comparison. As the reported case is heavily dependent on number of testings and other factors, rankings of individual countries in Fig. S1c differ to that from Fig. 9. Among SAARC countries, the ranking of Pakistan was highest for both the death and reported cases per million during that period (Fig. 9 and Fig. S1c).

Effect of temperature regionally and transition phase

Regional temperatures within a country can vary to a large degree (even ~ 25 °C for the USA, Fig. 2). Hence, vulnerability of any country will also depend on regional variations of temperature. In Fig. S2a, we showed that the southern part of Canada was mostly affected compared to the rest of the country. Interestingly, that region only lied in the most vulnerable temperature zone (Fig. 2c). A transition was noticed from March to April and more parts of southern Canada entered in moderately cold category in May indicting a rise in vulnerability. The spatial plot of Canada (Fig. S2a) and temporal pattern (Fig. S2b) indicated such features (Canada.ca 2020; Wikipedia 2020b). The daily death count increased during the beginning of April (Fig. S2b). A very high number of daily deaths were reported on the 1 May (Table 1, 6th column), which was comparable to most vulnerable countries.

In spite of a lockdown situation globally (Wikipedia 2020a), there was an increase in vulnerability to some countries that needs attention too. Since the end of April, many countries started moving from one vulnerability

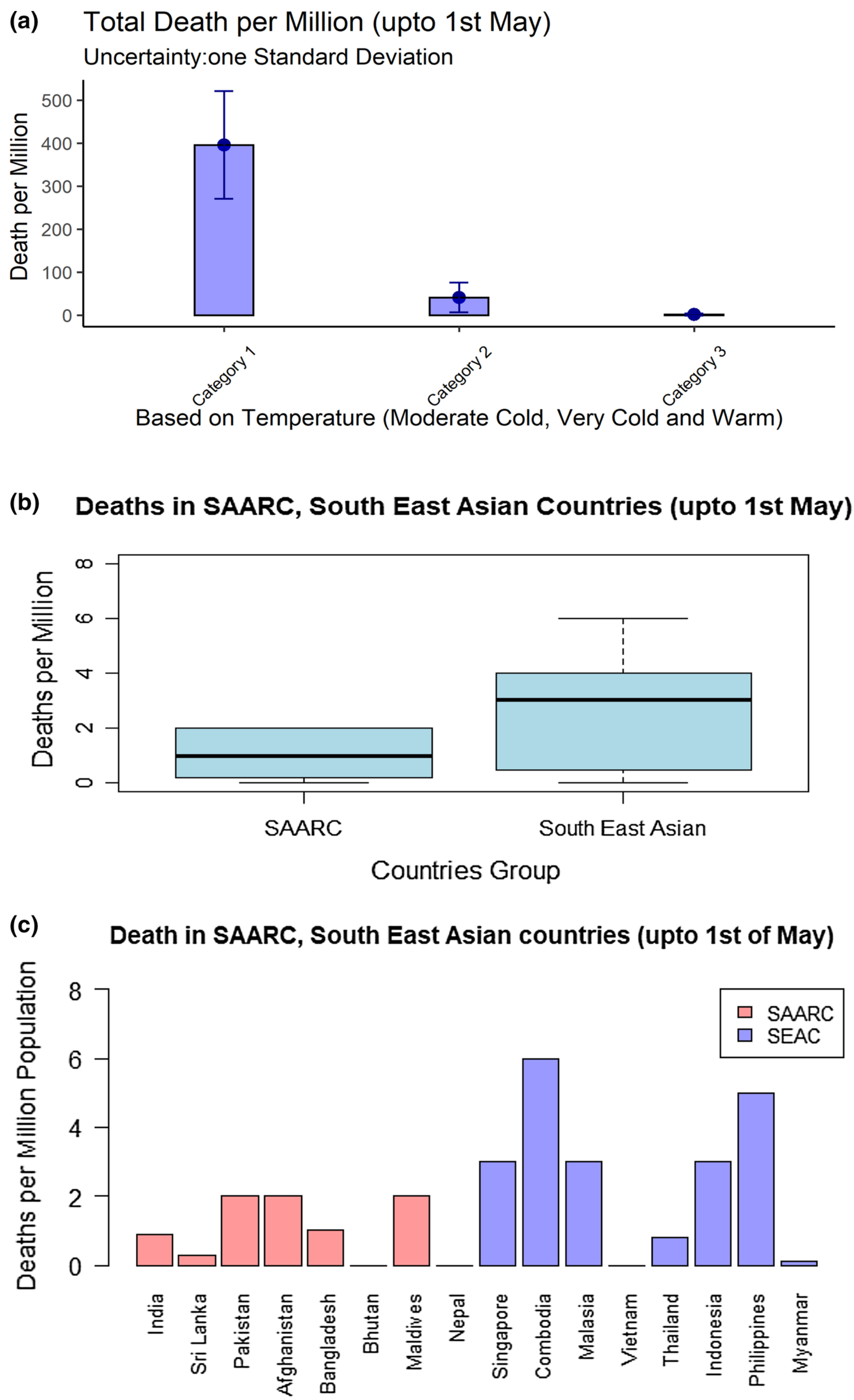

Fig. 9 Vulnerability to COVID-19 measured in terms of deaths per million, up to 1 May 2020. **a** Deaths in moderately cold, very cold and warm countries are shown. In category 3, all warm countries (SAARC and south-east Asian countries (SEAC), continents of Australia and Africa) together are presented. Uncertainty at one standard deviation level is marked. **b** Box plot with particular focus on SAARC and SEAC groups. **c** Record of each individual country from b

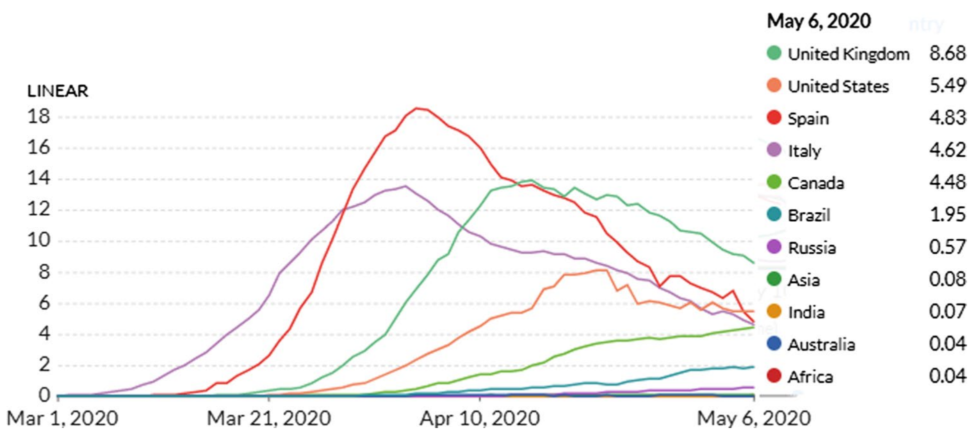

Fig. 10 Rolling 7-day average of daily confirmed COVID-19 deaths per million up to 6 May 2020 (Ourworldinddata 2020). India, Asia, Africa and Australia all are very low compared to the rest throughout and practically merges with X axis (hence not visible). The bottom three curves are for Russia, Brazil and Canada, respectively. All three are showing a rising trend. Top four high peak curves are for UK, USA, Spain and Italy. All four are currently in a declining state. Plot generated using: https://ourworldindata.org/grapher/daily-covid-deaths-per-million-7-day-average. Accessed 10 May 2020

state to others, e.g. Russia, Canada and some Scandinavian countries. For Russia, new cases reported on 7 May was 10,559, which was second-highest reported case after the USA (Worldometers 2020a). Canada also reported very high death on that day, which was 189, and again comparable with vulnerable countries (Worldometers 2020a). For Sweden, the death reported on 7 May was 87 which was relatively high compared to the overall population of 10,089,795 (Worldometers 2020a). Those countries were very cold in March and at the beginning of April and at later stages were seen phasing out to moderate cold phase.

A recent research (Scafetta 2020) studied the effect of temperature on the spread of COVID-19 in Italy. It showed only 2 °C rise in temperature can have a comparable effect on the transmission rate of virus. The effect of small change in temperature even for 2 °C to 2.5 °C was analysed and discussed for a few continents in Fig. S3 (Europe), Fig. S4 (Africa) and Fig. S5 (South America).

A spatial plot particularly focused on Europe (Fig. S3) suggested that UK was still in the most vulnerable zone in April, whereas southern Europe turned warmer (Fig. S3 a and b). Scandinavian countries like Sweden started entering into most vulnerability zone from moderate vulnerability state (Fig. S3 a and b). As Europe turned warmer from moderately cold, death rate decreased and the same pattern is observed till August.

For Africa, the region of least vulnerability was marked by dark red (Fig. S4). The temperature increased around latitude 10°N–15°N in April and Table 1 (6th column) showed no new death was reported to those countries. Questions could be raised about poor testing and reporting in those African countries. One reason could be that as death was reported zero, those underdeveloped countries may not have considered testing a priority. Moreover, in Australian continents without much of an issue of testing and reporting also suggested similarly. In fact, part of western Australia and northern territory (least vulnerable region, Fig. 2) did not have deaths and practically few reported cases (JHUM 2020) (hence not shown in Table 1). A shift in high temperature region in Africa from south to north during March to April gave an indication of how the vulnerability can shift regionally and gave rough time estimations of that transition. Northern territory of the continent turned warmer in April from March, while southern territory (that include south Africa) started to become cooler (Fig. S4).

As 2 °C change of temperature can influence the transmission of the disease (Scafetta 2020), this study wanted to confirm that for South America (Fig. S5). Some countries from South America suddenly started an increase in deaths and reported cases. On 7 May, Brazil reported new daily death 667, the second-highest after USA (Worldometers 2020a). The lowering of temperature in Southern Brazil (297 °C to 291 °C in April) is clearly distinct in Fig. S5b to that from Fig. S5a.

In terms of population, three highly populated countries are considered the USA, Brazil and India (world ranking 3rd, 6th and 2nd, respectively) (Worldometers 2020b). A plot of daily death till beginning of May was presented for those three countries (Fig. S6a). The USA, a vulnerable country, showed a very high daily count (Wikipedia 2020c), Brazil in a transition phase from warm to cooler state, suggested high death count with a comparatively steeper rise in very later periods (Wikipedia 2020d). India the less vulnerable country was moving from warm to warmer. It reported much less death count compared to the rest two (Wikipedia 2020e).

Temporal pattern of these three countries is also consulted up to August in Fig. S6b. They ranked 1st, 2nd and 3rd, respectively, globally in terms of total cases and daily deaths on 11 August 2020 (Worldometers 2020b). The USA peaked around April, and after a decline, it again started showing a rise in recent period (Worldometers 2020c). Brazil reached a peak at around June and still continued with that trend without a decline (Worldometers 2020d). India was showing a steady rise and did not reach a peak till August (Worldometers 2020e). The 7-day average showed the maximum count for India was the lowest, USA the highest, followed by Brazil.

Figure 10 shows daily confirmed COVID-19 deaths per million in the form of rolling 7-day average. Those statistics were consistent with the number of death counts per million (Table 1, 3rd column). There are clear distinctions throughout the time period among moderately cold, very cold and warm countries. All warm continents, e.g. Asia, Africa and Australia, those belonged to the less vulnerable category, suggested a very nominal daily death count rate compared to the rest (not visible as merges with X axis). The bottom three curves are for Russia, Brazil and Canada, respectively. All three were showing a rising trend and we discussed earlier those three were in the transition state. In later period, Russia and Canada were turning from very cold to moderate cold, whereas Brazil from warm to cold. For the USA, UK, Italy and Spain all suggested very high count throughout and all achieved a peak. Those are in declining states in the later period. During the declining phase, the temperature was also increasing.

Based on the discussion, it is possible to determine the vulnerability of a specific country as a whole and region-wise during different time periods. Another point is worth mentioning that this is an extremely contagious disease and single contamination through a foreign career/traveller can multiply exponentially among locals. Megapolises like New York, Mumbai, London are expected to be infected more than its suburb and it is, in fact, the case. All those factors were also considered while analysing the statistics.

Possible solutions

The above analyses highlighted that temperature plays an important role in transmissions of coronavirus (Seung et al. 2007; Yuan et al. 2006; Casanova et al. 2010; Chan et al. 2011; Van Doremalen et al. 2013) that include COVID-19 (Paulo 2020; Demongeot et al. 2020; Scafetta 2020). Warm temperature drastically reduced its impact. Hence, the following urgent measures (also mentioned earlier in Roy 2020a, b, c) are proposed to arrest and stop the outbreak:

(i) *Using the Sauna facility:* Usually hotels, gyms, leisure centres have existing Sauna facilities which people can start taking advantage of immediately. Mobile and Caravan Sauna facilities can also be thought of by higher authorities.After Sauna, if surfaces in public places are touched, hand washing is advisable.

(ii) *Portable Convector room heater:* People can be close to a convector room heater and inhale hot air at least two times a day for around half an hour each time (keeping comfort level). It would be very useful at the initial stages of the disease. Being portable in nature, it can be moved around and many people can avail that facility in a flexible way. Room heaters can also be useful for disinfecting purposes.

(iii) *Disinfect any place using high temperature:* Before the start and end of offices, school or business, the air-conditioned temperature of the premise may be kept, say, 60 °C for some time (say, half an hour) to disinfect. The optimal level (temperature and time) can be tested very easily. For airports, train and bus, that method of disinfecting could be useful. For any external object or material, disinfecting using high temperature could be a useful solution.

(iv) *Using Blow dryers (Hair dryer):* For minor symptoms, inhaling hot air intermittently through the nose (keeping comfort level) even for five minutes, say two/three times a day, will be useful to kill the virus in the nasal cavity.

(v) *Hot Drinks:* Hot drinks (could be tea, coffee, warm milk, hot water with lemon, etc.), hot soup, gargle with warm salt water few times a day to destroy virus in the mouth and throat.

The last two measures are proposed because the virus, which is very sensitive to temperature, mainly enters through the nose (WHO 2020) and initially accumulates in mouth and nose. Testing is done with swab from nasal cavity and

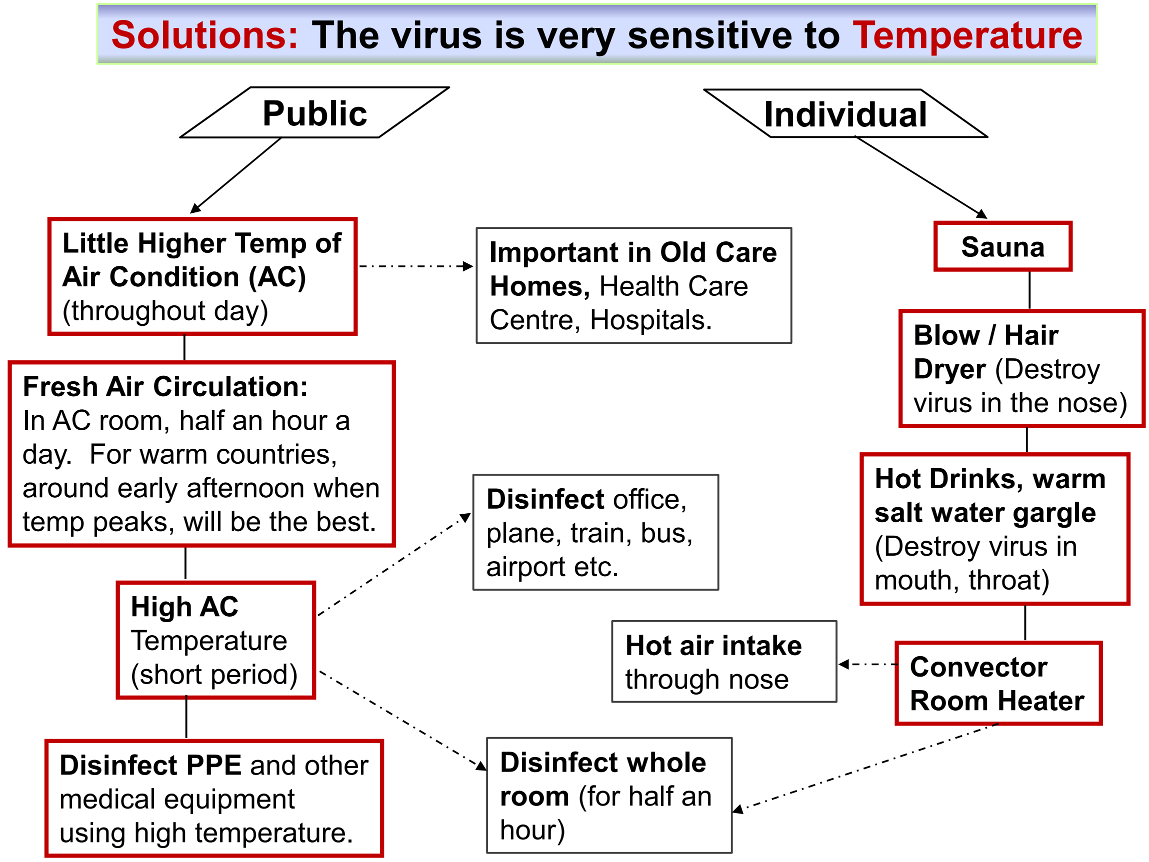

Fig. 11 An overview depicting actions towards Solutions at Individual level (right) and General or Public level (left) in the form of a schematic

back of the mouth. See, Master slide with simple Solutions: Master_Slide.pdf.

The main point in this analysis is that the virus is very sensitive to temperature. Based on that knowledge, these few measures are proposed. Many simple, easy procedures serving the purpose can be thought of; some could be applicable to warm countries and poor, remote, rural communities (discussed by the author AGU, 2020, Roy, iPoster; also in the Supplementary File S2: Paper_Presentation).

Study showed SARS-CoV-2 is more infectious than some other coronavirues (Ferretti et al. 2020). The virus can stay in the human body for a few days without showing symptoms though they still could be a carrier (WHO 2020; ECDC 2020b). As it is difficult to trace mild or presymptomatic infection, it has greater epidemic potential (Ferretti et al. 2020). These measures described above could be very effective when people are in the initial stage of the disease or in the asymptomatic or presymptomatic state. It is noteworthy that when people already developed major symptoms then this method will not be effective and proper medical advice need to be solicited. Given the emergency situation, lots of treatment/medicines are desperately tried which are fraught with risks of serious side effects. On the contrary, this solution has practically zero side effects. This study suggests the majority of world populations need to be well prepared before the coming winter. Social isolation and lockdown can be a temporary solution, as the economy and mental health also need attention. An overview depicting actions towards Solutions in the form of a schematic is presented in Fig. 11.

These measures, as mentioned, are likely to reduce the spread dramatically. If few of these measures are implemented worldwide, it will have a major impact to arrest the spread of the virus.

Conclusion

This article investigated the influence of temperature globally in the spread and vulnerability to COVID-19. It indicated that temperature was a crucial factor in transmitting the virus. For the spread of the virus, the most favourable state was moderately cool places, whereas warm countries and places were likely to be less vulnerable. Similar temperature dependency was also noticed in previous clinical trials those involved other coronavirus (MARS, SARS, etc.) and seasonal influenza/flu virus. Four different categories of vulnerability were identified based on temperature variations—which were moderate cold, very cold, moderately warm and very warm. For analysing vulnerability, death per million population was considered as a useful and effective metric. The maximum reported case, as well as death, was noted when the temperature was between the threshold of around 275 °K (2 °C) and 290 °K (17 °C). Based on temperatures of March and April, some countries were specified too; the USA, UK, Italy, Spain belonged to this category. The vulnerability was moderate when the temperature was less than 275 °K (2 °C) and countries in that category for March and April were Russia, parts of Canada and Scandinavian countries. A significantly lesser degree of vulnerability was noted for countries with temperatures 300 °K (27 °C) and above (maximum temperature up to April was around 310 °K). SAARC countries, southeast Asian countries (SEAC), African continent and Australia belonged to that category during March and April. In fact, when the temperature was more than 305 °K (32 °C) there was an unusually very low number of reported cases as well as deaths. Some parts of Australia and African continent showed such behaviour in March and April. The vulnerability to the disease was significantly different, between each other, for moderately cold, severe cold and warm countries. For warm countries, further analyses on the group of SAARCs and SEAC were conducted and individual countries were also compared.

Maps based on temperature were presented to identify countries of different vulnerability state in different months of the year. It discussed that based on temperature variation, countries can move from one vulnerability state to the other. For example, parts of Russia and Canada started entering from severe cold to moderate cold state at the end of April, whereas Brazil and few warm countries from South America moved from warm to less warm state. In spite of lockdown situation worldwide, those countries reported a sudden rise of death and infected cases at the beginning of May.

This study also discussed daily confirmed COVID-19 deaths per million over the period, in the form of rolling 7-day average. It was consistent with the number of total death counts per million. There were clear distinctions throughout the time period among moderately cold, very cold and warm countries. All warm continents, e.g. Asia, Africa and Australia, those belonged to a less vulnerable category, suggested a very nominal daily death count rate compared to the rest. The USA and European countries showed a decline in the later period, while Russia, Canada and Brazil showed a rise.

This analysis can also give some idea for regional variation of vulnerability of various countries and specifically discussed that for Canada. Spatial variation within continents was discussed for Europe, South America and Africa for the month of March and April. This study could indicate which countries are in advantageous/disadvantageous state in the coming months based only on temperature variation. As regional temperature plays a very important role in the transmission and spread, these results and future predictive maps have a major implication for future planning.

This study discussed that, like other similar category viruses, this virus is also very sensitive to temperature. It gave a valuable insight that regulating temperature level can provide a useful strategy to arrest and stop the outbreak. Based on that knowledge, some urgent solutions are proposed. It is very cost-effective and practically without side effects. To adopt these solutions, no vast amount of funding is required. Another novelty of such an approach is that it can be implemented immediately across the globe. These measures are likely to reduce the spread of the disease dramatically.

Acknowledgement This study did not receive any funding, and there is no conflict of interest (financial or non-financial). Figures 2, 3, 4, 5, 6, 7, 8 and Fig. S3–S5 are generated from the NOAA/ESRL Physical Sciences Division, Boulder Colorado website at https://psl.noaa.gov/data/composites/day/. It has few preprint versions and the first preprint version that mentioned solutions (Roy 2020a: https://doi.org/10.13140/rg.2.2.22632.83208) was published on 17 March 2020.

Funding This study did not receive any funding.

Availability of data and material All data used are openly available and relevant websites are mentioned.

Compliance with ethical standards

Conflict of interest There is no conflict of interest.

References

AGU (American Geophysical Union), Roy, I, (2020) iPoster, 'Influence of Temperature on the global spread of COVID-19'. https://covid19covenv-agu-azure.ipostersessions.com/default.aspx?s=4F-D9-45-B2-4C-B0-2A-F4-10-B5-71-05-DA-1D-45-4D. Accessed 2 Nov 2020

Canada.ca (2020) Government of Canada. https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection.html. Accessed 2 May 2020

Casanova LM, Jeon S, Rutala WA, Weber DJ, Sobsev MD (2010) Effects of air temperature and relative humidity on coronavirus survival on surfaces. Appl Environ Microbiol 76(9):2712–2717. https://doi.org/10.1128/aem.02291-09

Chan KH, Peiris JS, Lam SY, Poon LL, Yuen KY, Seto WH (2011) The effects of temperature and relative humidity on the viability of the SARS coronavirus. Adv Virol 2011:734690. https://doi.org/10.1155/2011/734690

Chen Y, Li L (2020) SARS-CoV-2: virus dynamics and host response. The Lancet 20:5. https://doi.org/10.1016/S1473-3099(20)30235-8

Demongeot et al (2020) Temperature decreases spread parameters of the new COVID-19 Case Dynamics. Biology 9:94

ECDC (2020b) COVID-19 Questions-answers. https://www.ecdc.europa.eu/en/covid-19/questions-answers. Accessed 8 May 2020

ECDC (European Centre for Disease Prevention and Control) (2020a) COVID-19. https://www.ecdc.europa.eu/en/geographical-distribution-2019-ncov-cases. Accessed 03 April 2020

Ferretti L et al (2020) Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science. https://doi.org/10.1126/science.abb6936

Fuhrmann C (2010) The effects of weather and climate on the seasonality of influenza: what we know and what we need to know. Geogr Compass 4(7):718–730. https://doi.org/10.1111/j.1749-8198.2010.00343.x

Gorbalenya AE, Baker SC, Baric RS et al (2020) The species Severe acute respiratory syndrome-related coronavirus: classifying 2019-nCoV and naming it SARS-CoV-2. Nat Microbiol 5:536–544. https://doi.org/10.1038/s41564-020-0695-z

JHUM (Johns Hopkins University of Medicine) (2020) Coronavirus resource centre. https://coronavirus.jhu.edu/map.html. Accessed 03 April 2020

Kalnay et al (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteor Soc 77:437–470

Li Q, Guan X, Wu P et al (2020) Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. N Engl J Med 382(13):1199–1207. https://doi.org/10.1056/nejmoa2001316

Lipsitch M, Viboud C (2009) Influenza seasonality: lifting the fog. Proc Natl Acad Sci 106(10):3645–3646

Lowen AC, Mubareja S, Steel J, Palese P (2007) Influenza virus transmission is dependent on relativehumidity and temperature. Plos Pathogens 3(10):1470–1476. https://doi.org/10.1371/journal.ppat.0030151

Ourworldinddata (2020). https://ourworldindata.org/grapher/daily-covid-deaths-per-million-7-day-average. Accessed 10 May 2020

Paulo M et al. (2020) Effects of temperature and humidity on the spread of COVID-19: a systematic review. Plos One

PSL (Physical Sciences Laboratory) (2020) https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.derived.html. Accessed 8 May 2020

Roy I (2020a) Combating recent pandemic of COVID-19-an urgent Solution. https://doi.org/10.13140/rg.2.2.22632.83208 also, https://www.preprints.org/manuscript/202003.0366/v1. Accessed 17 March 2020

Roy I (2020b) Atmospheric variables and additional urgent solutions for combating COVID-19 dt 9th April. https://www.preprints.org/manuscript/202003.0366/v2

Roy I (2020c) Influence of temperature on the global spread of COVID-19' dt 21st June. https://www.preprints.org/manuscript/202003.0366/v3

Scafetta N (2020) Distribution of the SARS-CoV-2 pandemic and its monthly forecast based on seasonal climate patterns. Int J Environ Res Public Health 17(10):3493. https://doi.org/10.3390/ijerph17103493

Seung WK, Ramakrishnan MA, Raynor PC, Goyal SM (2007) Effects of humidity and other factors on the generation and sampling of a coronavirus aerosol. Aerobiologia 23:239–248. https://doi.org/10.1007/s10453-007-9068-9

Shaman J, Kohn M (2009) 'Absolute humidity modulates influenza survival, transmission, and seasonality. Proc Natl Acad Sci 106(9):3243–3248. https://doi.org/10.1073/pnas.0806852106

Van Doremalen N, Bushmaker T, Munster VJ (2013) Stability of Middle East respiratory syndrome coronavirus (MERS-CoV) under different environmental conditions. Euro Surveill 18(38):20590. https://doi.org/10.2807/1560-7917.ES2013.18.38.20590

WHO (World Health Organisation) (2020) Emergencies, diseases. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/naming-the-coronavirus-disease-(covid-2019)-and-the-virus-that-causes-it. Accessed 8 May 2020

Wikipedia (2020a) National_responses _to_the _COVID-19_pandemic. https://en.wikipedia.org/wiki/National_responses_to_the_COVID-19_pandemic. Accessed 8 May 2020

Wikipedia (2020b) https://en.wikipedia.org/wiki/2020_coronavirus_pandemic_in_Canada. Accessed 2 May 2020

Wikipedia (2020c) https://en.wikipedia.org/wiki/2020_coronavirus_pandemic_in_the_United_. Accessed 2 May 2020. States

Wikipedia (2020d) https://en.wikipedia.org/wiki/2020_coronavirus_pandemic_in_Brazil#April_. Accessed 2 May 2020

Wikipedia (2020e) https://en.wikipedia.org/wiki/2020_coronavirus_pandemic_in_India#April_2020. Accessed 2 May 2020

Worldometers (2020a) Coronavirus. https://www.worldometers.info/coronavirus/#countries. Accessed 2 May 2020

Worldometers (2020b) World-population. https://www.worldometers.info/world-population/population-by-country/. Accessed 7 May 2020

Worldometers (2020c) Coronavirus, Country, US. https://www.worldometers.info/coronavirus/country/us/. Accessed 11 Agu 2020

Worldometers (2020d) Country, Brazil. https://www.worldometers.info/coronavirus/country/brazil/. Accessed 11 Agu 2020

Worldometers (2020e) Country, India. https://www.worldometers.info/coronavirus/country/india/. Accessed 11 Agu 2020

Yuan J, Yun H, Lan W, Wang W, Sullivan SG, Jia S, Bittles AH (2006) A climatologic investigation of the SARS-CoV outbreak in Beijing, China. Am J Infect Control 34(4):234–236