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Seasonal Effect of Sunlight on COVID-19 among Countries with and without Lock-Downs

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Abstract

Objective: The main aim of the study was to determine whether COVID-19 epidemiological data reported by countries in different hemispheres correlated with the seasons of the year. Since stay-at-home orders could be a main factor affecting the time individuals spent outdoors, the progression of COVID-19 in countries that mandated the most stringent lock-downs and stay-at-home orders was compared to countries in the same hemisphere that did not order their citizens to remain at home. Methods: Infections attributed to COVID-19 per million inhabitants, deaths per infections × 100, and deaths per million inhabitants from different countries were analyzed utilizing national reports registered in the Johns' Hopkins database together with the most recent world population data. The null hypothesis (no difference between countries with and without lock-downs) was tested (two tailed test, $p < 0.01$) for each paired set of data according to well established statistical analysis. Results: The shift of highest infection rates from countries in the northern-towards countries in the southern-hemisphere during early 2020 and the reverse in December of the same year correlates with the seasonal variation in the flux of germicidal sunlight. Mortality rate for the same virus among different countries did not show a seasonal component. COVID-19 infection mortality rate was considerably lower in developing countries of South America (11 of the largest countries) than in several (at least 8) developed European countries. Discussion: COVID-19 resulted in higher infections during winter than in summer. The finding of a seasonal component, correlating the progression of the pandemic with local solar flux, demonstrates that infectious virus in the environment plays a role in the pandemic since direct person-to-person transmission would afford little time for solar inactivation. Similar epidemiological data amongst "locked" and "unlocked" countries demonstrates that lock-downs and similar confining measures had no effect on the chances of healthy individuals becoming infected with SARS-CoV-2 or dying of COVID-19.

Keywords

SARS-CoV-2, COVID-19, Coronaviruses, Global Health, Environmental Health, Quarantine, Lock-Down, Epidemic, Pandemic, Virus Inactivation, Solar Radiation, Seasonal Progression, COVID-19 Photobiology

1. Introduction

The world has witnessed many epidemics in the past [1]. Other coronaviruses like SARS and MERS produced pandemics that started in 2002 and 2012, respectively [2] [3]; and coronaviruses cause 15% - 20% of all upper respiratory infections in humans, even in the absence of epidemics [4]. Several other viruses, like those of relevance in biodefense (with mortality rates of 40% for Lassa virus and 53% to 92% for Sudan and Zaire strains of Ebola virus, respectively [5]) cause higher mortality than SARS-CoV-2 (global mortality rate of COVID-19 based on number of infections averaged 3.1% (with deaths per million approaching 0.012% globally)) as of 22 September, 2020 [6]. Rather what has been unusual were predictions made by computer modeling of 7 billion infections and 40 million deaths during 2020 alone if quarantine, lock-downs and other highly restrictive measures were not enforced [7]. These predictions may have been instrumental [8] in justifying 1168 quarantine and lock-down policies mandated by governments of 165 countries [9] that confined indoors at-risk as well as healthy individuals, resulting in an economic and social crisis without historical precedents.

It is well known that there is direct transmission of infectious virions by inhalation of contaminated aerosols exhaled, coughed, or sneezed from infected persons and this direct (person-to-person) transmission was shown to be important in transmission of SARS-CoV-2 between nearby individuals [10]. The main non-pharmaceutical measures to control the pandemic, ranging from the relatively benign (like wearing face masks or social distancing) to the highly restrictive (like quarantine, curfews, stay-at-home orders or lock-downs) all intended to prevent direct, person-to-person transmission of disease. Remarkably, these measures did not halt COVID-19, rather the pandemic progressed at a sustained rate despite reports of 1.7 billion under some form of indoor confinement from March 26, 2020, that increased to 3.9 billion people by the first week of April 2020 which amounts to more than half of the world's population in quarantine or in-house lock-downs [11] [12]. The relative failure of measures intended to control direct person-to-person transmission suggests that an additional source of contagion (like infection from contaminated environments) could be playing a role in the COVID-19 pandemic.

While the viral load of SARS-CoV-2 in exhaled breath of infected individuals remains uncertain, high loads of genomic material have been detected in upper respiratory tract specimens of COVID-19 infected patients in throat and nasal swabs [13] [14] [15]. SARS-CoV-2 is relatively stable when suspended in aerosolized micro-droplets [16] [17]. Micro droplets of respirable size can reach distances of 12.5 meters (over 40 feet) [18]. Influenza virus was readily re-aerosolized by sweeping floors without much loss in infectivity [19] and it should be assumed that SARS-CoV-2 will be reaerosolized in a similar manner. SARS-CoV-2, at a starting viral load and in a fluid matrix equivalent to that typically excreted by infected patients, remains viable or infectious for at least 21 to 28 days when dried onto non-porous surfaces at 20˚C and 50% relative humidity [20] [21]. Research on the original SARS virus also showed recovery of the infectious virus when dried on plastic for up to 28 days at room temperature and 40% - 50% RH [22]. These laboratory findings suggest that SARS-CoV-2 should be able to persist for long periods in aerosols or onto contaminated environments but an alternative route of infection other than direct (person-to-person) contagion has not been established.

COVID-19's persistence outdoors can be generally attributed to three main physical factors: temperature, humidity, and the contribution of the germicidal (UVB) component in sunlight radiation. Laboratory experiments have demonstrated a rather limited effect on SARS-CoV-2 survival due to changes in relative humidity [23]. Colder average monthly temperature was not associated with higher levels of COVID-19 mortality when accounting for other independent variables [24]. Although some controversy remains, the main evidence suggests a limited effect of changes (within the environmental range) in relative humidity and temperature on the persistence of SARS-CoV-2 [23] [24], similar to that previously reported on the influenza virus [25] [26] [27] [28] [29].

Ultraviolet radiation in sunlight is the primary virucidal agent in the environment [30] [31] [32] and viral inactivation by natural sunlight has been documented [33] [34]. The effect of the seasons of the year (with winter more morbid than summer) on influenza pandemics has been well established [25] [27] [28]. The UV sensitivity of coronaviruses, in general, and of SARS-CoV-2 in particular, indicates that 90% or more of SARS-CoV-2 virus should be inactivated after being exposed for 11 - 34 minutes of midday sunlight during summer in most cities worldwide [35]. This rate of inactivation by natural sunlight agrees with laboratory experiments using solar simulators where 90% of airborne SARS-CoV-2 was inactivated after 19 minutes or 8 minutes of simulated sunlight corresponding to standardized fluences expected during late winter/early fall or summer, respectively [23]; and 6.8 minutes in simulated saliva or 14.3 minutes in culture media under simulated sunlight during the summer solstice [36]. In contrast, the virus should persist infectious for a day or more in winter (December-March in the northern hemisphere), with potential risk of re-aerosolization and transmission at the same locations [35]. Considering that SARS-CoV-2 could be three times more sensitive to UV than influenza A [35] [37], it should be inferred that sunlight should have an effect on coronaviruses transmission at least similar to that previously established for the evolution of influenza epidemics [27] [28] [33].

The main aim of the present study was to determine any correlation between solar radiation and COVID-19 progression before vaccination could have affected the progression of the pandemic. Such a correlation should indicate a role for contaminated environments from where SARS-CoV-2 could be transmitted after re-aerosolization or contact. The persistence of the virus in contaminated environments would afford enough time for sunlight inactivation if direct person-to-person transmission were not the only route of contagion.

2. Methods

The total number of infections and deaths attributed to COVID-19 need to be normalized for comparative purposes (everything being equal, large populations should have larger number of cases). Therefore, infections attributed to COVID-19 per million inhabitants (infection rate) and deaths per infections × 100 (infection mortality rate) from different countries were considered in this study. However, infection mortality rates are strongly affected by the number of infections, which in turn varies with the level of testing. Serological testing uncovered relatively high numbers of asymptomatic cases, thus decreasing the infection mortality rate [38]. Therefore, the deaths per million inhabitants (population mortality rate) were also included in this analysis utilizing the 2019 world population data [39]. Among available sources, the epidemiological data for the COVID-19 pandemics from John's Hopkins' Center for Systems Science and Engineering [6] was employed. The reported mortality attributed to COVID-19 is not "excess mortality" as usually recorded in epidemiology; therefore, the mortality figures used here could be an overestimation if basal mortality (mortality occurring in absence of epidemics) would be discounted. A map, as well as a list of countries and territories that did not mandate lock-downs can be freely downloaded from the world-wide-web [40] [41] [42] [43] [44]; and a summary of countries with- and without lock-downs was also published elsewhere [45]. The figures corresponding to infection per million inhabitants were pooled for countries that instituted lock-downs in each continent. The same was done for "unlocked" countries in each continent. The null hypothesis (no difference between countries with and without lock-downs in each continent) was tested (two tailed test, $p < 0.0100$) for each set of data according to well established statistical analysis [46] [47] using an online calculator [48].

The list of U.S. states and cities that ordered residents to stay at home has been previously reviewed [49]. The dates in which lock downs and quarantines came into effect (before 22 March, 29 March, 5 April, or 12 April, 2020) in various U.S. States have been monitored [50]. Infection rate (cases per million inhabitants) in U.S. states was calculated by dividing the reported number of cases attributed to coronavirus [51] [52] by the state population (in millions to one decimal point) using the 2019 Census estimates taken by the United States Census Bureau [53]. For each US state tabulated, in addition to infection attributed to COVID-19 per million inhabitants, the 7-day moving average deaths per million inhabitants is shown [54]. Graphs showing progression of COVID-19 used the specific data sets reported for the countries shown [6] [55] [56].

3. Results

3.1. COVID-19 Seasonal Component

A progressive increase in infections per million inhabitants can be seen in **Table 1** within the studied period for all countries (with or without lock-downs). The data in bold numbers presented in **Table 1** indicates at least, a 4-fold increase in either infections per million inhabitants or in (infection or population) mortality rates between the previous and subsequent dates shown. A considerable (4-fold) increase in infection per million inhabitants occurred in only one country (India) out of 12 represented countries in the northern hemisphere between 29 May and 21 July, 2020. In contrast, all studied countries in South America and Africa, except one (Uruguay) reported at least a 4-fold increase between fall and beginning of winter in the southern hemisphere.

Of the 30 countries with highest COVID-19 according to data reported on May 7, 2020 [6], 28 were located north of the Tropic of Cancer (the two exceptions being equatorial Qatar and Mayotte at latitudes 25˚N and −13˚S, respectively). The epidemiological data reported on July 21, 2020 from the same source shows that the composition of the 30 countries with highest incidence had changed. On July 21, of the 30 countries with highest infection per million inhabitants only 14 countries where still located in the northern hemisphere, 11 countries were equatorial (located within latitude ± 26˚) and 5 countries (Chile, Peru, Brazil, Bolivia and South Africa) were located in the southern hemisphere. These data indicates that the highest incidence of COVID-19 infection progressed from countries in northern latitudes, where it was winter at the beginning of the pandemic, to countries in the southern hemisphere where it was winter on July 21. This seasonal progression correlates with the variation in the virucidal solar flux received by several of these countries previously reported [35]. As of 7 September 2020, the location of the 30 countries with highest incidence of COVID-19 has dispersed north and south of the equator without an obvious geographical pattern. On 14 December the composition of the 30 countries with highest number of infections has changed again, with only six countries in the southern hemisphere where summer is starting and 24 countries in the northern hemisphere where sunlight radiation has been decreasing due to incoming winter. The relative increase of infections through the year 2020 correlates with a differential progression of COVID-19 between countries in northern and southern hemispheres following the respective seasonal shift from- and into-winter.

3.2. Stay-at-Home Orders and Lock-Downs

The seasonal effect of sunlight radiation on COVID-19 epidemiology was

Table 1. (a) Countries[1] that mandated nation-wide lock-down. The table shows infected per million[2], mortality rate as (% of infected)[3] and total deaths [per million inhabitants] attributed to COVID-19; (b) Countries without lock-down[3]. The table shows infected per million inhabitants, deaths per infections (×100) and [deaths per million inhabitants][4] attributed to COVID-19.

(a)

	29 MAY	21 JULY	7 SEPT	26 OCT	14 DEC
Europe[A]					
Spain	6096 (9.5%) [581]	6700 (9.1%) [609]	11,240 (5.6%) [632]	24,732 (3.0%) [750]	37,240 (2.7%) [1020]
UK	3966 (14.1%) [565]	4356 (14.5%) [673]	5152 (13.3%) [692]	13,157 (5.2%) [692]	27,179 (3.5%) [951]
Italy	3832 (14.3%) [549]	4048 (14.3%) [580]	4612 (12.8%) [588]	8982 (6.9%) [619]	30,713 (3.5%) [1076]
Greece	332 (5.6%) [17]	388 (4.9%) [19]	1120 (2.5%) [28]	3027 (1.8%) [55]	***12,036 (2.9%) [355]***
Slovakia	311 (1.6%) [5]	377 (1.4%) [5]	849 (0.8%) [7]	8269 (0.4%) [30]	***24,445 (0.9%) [221]***
Latin America					
Chile	4552 (1.0%) [50]	***17,500 (2.6%) [457]***	22,159 (2.7%) [613]	26,272 (2.8%) [737]	29,902 (2.8%) [830]
Peru	4306 (2.9%) [130]	10,974 (3.8%) [418]	20,873 (4.3%) [918]	26,837 (3.8%) [1052]	29,687 (3.7%) [1105]
Argentina	326 (3.5%) [12]	***3010 (1.8%) [56]***	***10,576 (2.1%) [226]***	24,061 (2.6%) [654]	33,012 (2.7%) [898]
Asia					
India	123 (2.9%) [4]	***866 (2.4%) [21]***	3094 (1.7%) [53]	5740 (1.5%) [88]	7145 (1.5%) [104]
Thailand	59 (1.9%) [0.8]	47 (1.8%) [0.8]	49 (1.7%) [0.8]	54 (1.6%) [0.8]	61 (1.4%) [0.9]
Malaysia	239 (1.5%) [4]	272 (1.4%) [4]	292 (1.4%) [4]	858 (0.8%) [7]	2618 (0.5%) [13]
Africa					
South Africa	463 (2.1%) [11]	***6433 (1.4%) [92]***	10,756 (2.3%) [256]	12,037 (2.7%) [324]	14,435 (2.7%) [390]

(b)

	29 MAY	21 JULY	7 SEPT	26 OCT	14 DEC
Europe[A]					
Belaruse	4314 (0.5%) [24]	7040 (0.8%) [54]	7729 (1.0%) [76]	9918 (1.0%) [102]	17,162 (0.8%) [135]
Sweden	3614 (11.9%) [435]	7737 (7.7%) [565]	8562 (6.7%) [584]	10,929 (5.4%) [593]	31,607 (2.3%) [742]
Latvia	595 (2.7%) [13]	635 (2.6%) [16]	759 (2.4%) [18]	2531 (1.3%) [32]	***13,793 (1.4%) [352]***
Estonia	1430 (3.6%) [52]	1555 (3.4%) [53]	1948 (2.7%) [53]	3406 (1.6%) [56]	***14,142 (0.8%) [114]***
Lithuania	615 (4.1%) [25]	741 (4.0%) [30]	1148 (2.8%) [32]	4055 (1.2%) [50]	***35,027 (0.9%) [305]***
Latin America					
Mexico	378 (11.1%) [71]	***2762 (11.3%) [309]***	4908 (10.7%) [529]	6889 (10.0%) [594]	9650 (9.1%) [880]
Uruguay	234 (2.7%) [6]	315 (3.0%) [9]	483 (2.7%) [13]	820 (1.9%) [13]	2790 (0.9%) [26]
Nicaragua	115 (4.6%) [5]	***519 (3.1%) [16]***	703 (3.0%) [21]	817 (2.9%) [23]	884 (2.8%) [24]
Asia					
Indonesia	92 (6.0%) [6]	335 (4.9%) [16]	719 (4.1%) [30]	1432 (3.4%) [50]	2268 (3.0%) [69]
Japan	132 (5.2%) [7]	204 (3.8%) [8]	565 (1.9%) [11]	768 (1.8%) [14]	1422 (1.4%) [20]
South Korea	222 (2.4%) [5]	269 (2.1%) [6]	415 (1.6%) [7]	506 (1.8%) [9]	848 (1.3%) [11]
Africa					
Namibia	9 (0%) [0]	***537 (0.5%) [2]***	***3456 (1.0%) [36]***	4960 (1.0%) [53]	6530 (1.0%) [64]

[1]Countries were selected among those that mandated earlier, longer, and strictly enforced lock-downs, or that did not instituted lock-downs or similar restrictions [44] [45], thus being considered among the best known country representatives of its class. [2]Infections per million inhabitant, infection death rate (total deaths/infections × 100) shown in parenthesis ( ), were obtained from [6] on the dates of the year 2020 indicated in the Table. Population mortality rate shown by numbers between brackets [ ] were calculated by dividing total deaths [6] by the population (in millions to one decimal point) according to the 2019 census [39]. [3]The null hypothesis was tested by comparing the infections per million in both groups by using an online calculator [48] based on long established statistical methodology [46] [47]. [4]Bold figures indicate that either infection per million inhabitants or deaths per million inhabitants increased more than 4-fold from the preceding date.

studied through most of 2020 in a set of countries and of US states that did not mandate stay-at-home orders or lock-downs (thus providing maximal potential for staying outdoors with concomitant exposure to sunlight) in comparison to another set of countries and US states that instituted the most restrictive stay-at-home measures (thus, minimizing mobility and the potential for solar exposure). **Table 1** shows the number of infections attributed to COVID-19 per million inhabitants (infection rate), deaths per infections × 100 (infection mortality rate) as well as deaths per million inhabitants (population mortality rate) at various dates of the year 2020 for each country. The number of countries in the Table may be limited but they are among the best representatives of each group on each continent, and have broad differences in the incidence of infection. Regardless of further expanding the list of countries and the predicted or real effect of potential confounding factors, lock downs and other restrictive measures should have been justified by any evident and significant difference between the two groups in **Table 1**.

Unexpectedly, the statistical analysis described in Methods demonstrated no difference (significance level $p < 0.01$) in the number of infections per million inhabitants between countries that instituted early long-lasting nation-wide stay-at-home orders versus countries that did not. Similar conclusions can be intuitively drawn by simply perusing the dispersion of data in **Table 1**, as well as the comprehensive epidemiological database [6]. For example, among European countries in **Table 1** showing the lowest infection incidence when summer was ending (7 September) Greece, which instituted the most strict quarantine measures {infections 1120/million, deaths per infections (2.5%), and [28] deaths per million} and Slovakia {849/infections per million inhabitants, (0.8% deaths per infections), and [7 deaths per million inhabitants]} which was among the first countries to mandate quarantine, actually have figures not too different to those in Latvia {759/million, (2.4%), [28]} or Lithuania {1148/million, 2.8, [32]} which did not implement quarantine. Similarities can be seen in **Table 1(a)** and **Table 1(b)** also among countries with higher infection per million inhabitants in other continents.

Twenty-eight of the 30 countries with highest infections rates on 14 December, 2020 [6] mandated nationwide lock-downs or instituted stay-home orders (the two countries that did not order lock-downs among these being Mexico and Indonesia). Four fold increases in infections occurred also during the fall in the southern hemisphere (May-July) after Chile had imposed partial curfews and Peru and Argentina initiated stringent and long lasting stay-at-home orders between 16-19 March [45] [57]. Moreover, the nearly two-fold increase (or more) in infection per million inhabitants recorded between 7 September and 26 October among all the European countries in **Table 1** that instituted lock-downs correlates with the solar progression from summer into winter indicating that lock-downs were not able to eliminate the seasonal effect on the pandemic as was hypothesized at the beginning of the present study.

The data reported for those states of the U.S. that instituted early lock-downs and states that did not confine the population indoors [49] [50] also fails to show any statistically significant benefit of quarantine or lock-downs for the whole studied period (**Table 2**). The data on 26 October, after the summer ended, suggests a beneficial effect of stay-at-home orders (in average, around 40% less infections per million inhabitants among the analyzed US states that mandated lock-downs) but the difference is not statistically significant ($p = 0.0147$) within the constraints described in Methods (two-tailed T-test, $p < 0.0100$). Similarly, there are no differences in infections between US states with- or without-lock-downs on 14 December, 2020 at the $p < 0.0100$ level (two tailed test, p-value is 0.117).

The ranking of countries with highest infection per million inhabitants through the period studied, together with the data presented in **Table 1** demonstrates that, irrespective of confounding variables that could have an effect on the pandemic; stay-at-home orders, quarantines or lock-down fail to show any statistically significant benefit of imposing these restrictive and costly measures to the population.

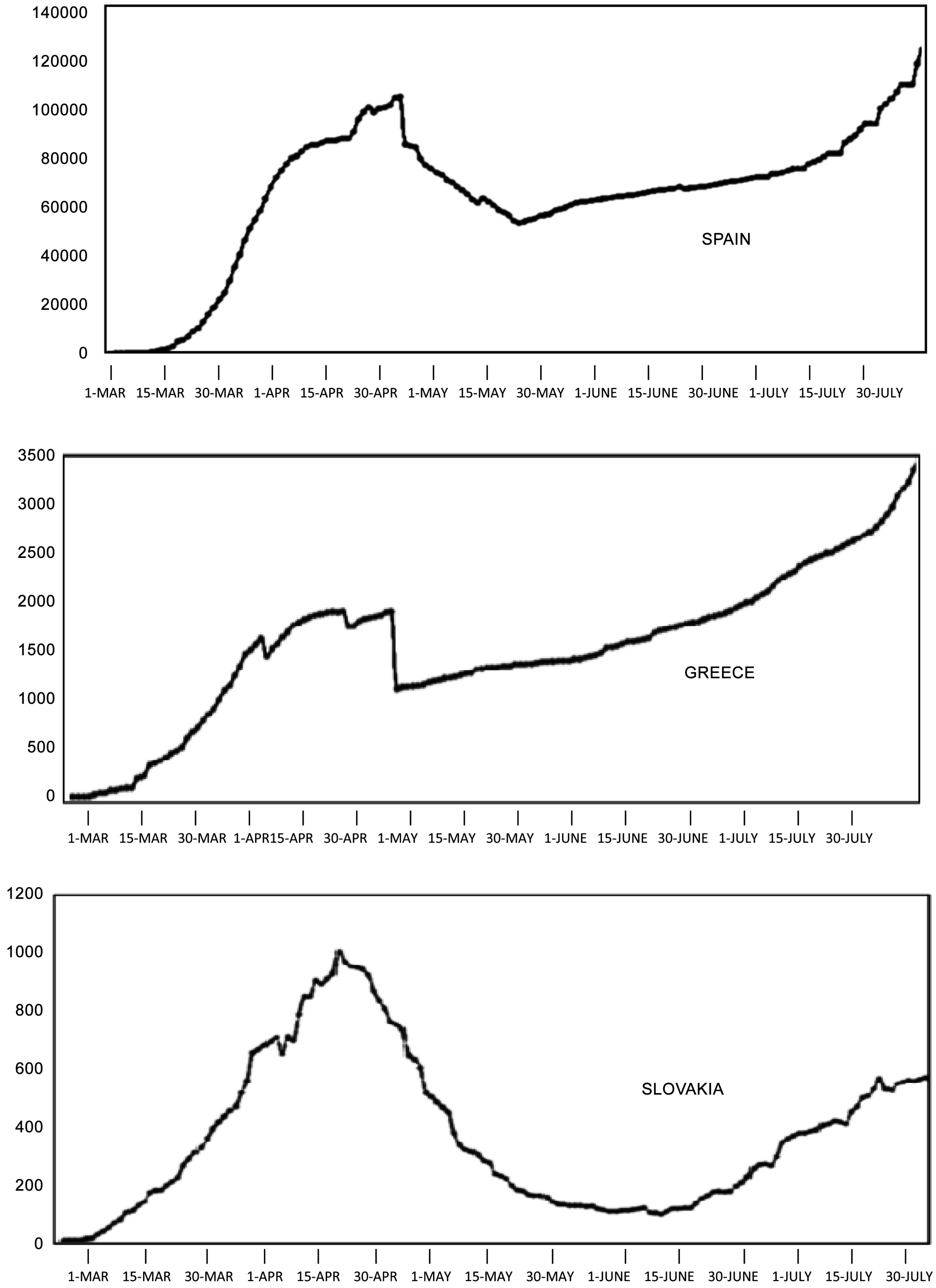
3.3. New Spikes of Infections

An understanding of COVID-19 must include a plausible explanation for the new waves of infections that resulted in spikes in the epidemiological data. **Figure 1** shows the number of active cases as a function of date according to national reports [6] from representative European countries listed in **Table 1**. Greece was among the earliest countries to mandate lock downs and Spain implemented some of the most restrictive lock down measures in Europe [55]. In

Table 2. The table shows infection per million inhabitants[1] and mortality (as weekly moving average and as daily deaths per million[2,3] attributed to COVID-19 in selected states of the USA.

	29 MAY	1 JULY	21 JULY	7 SEPT	26 OCT	14 DEC
That Mandated Early Lock-downs[4]						
New York	18,886 {4.3}	15,998 {0.6}	20,932 {0.5}	22,565 {0.2}	25,110 {0.6}	39,957 **{4.8}** [18.3]
New Jersey	17,847 {9.2}	19,318 {3.8}	19,916 {2.1}	21,841 {0.7}	25,130 {1.3}	45,017 **{6.9}** [20.0]
Illinois	9248 {6.3}	9546 {2.0}	12,983 {1.1}	19,913 {1.8}	28,310 {3.3}	66,843 **{13.8}** [12.1]
California	2630 {1.6}	5978 {1.7}	10,364 {2.4}	18,613 {2.9}	22,450 {1.4}	40,174 {4.0} [5.3]
That Did Not Mandate Early Lock-downs[4]						
Nebraska	6979 {1.6}	10,093 {1.3}	12,025 {1.3}	18,887 {0.9}	*31,180 {3.5}*	78,348 **{12.6}** [7.1]
Iowa	5914 {4.4}	9203 {1.1}	12,336 {1.7}	22,001 {2.4}	35,010 {5.0}	80,078 **{24}** [10.2]
Arkansas	2179 {0.6}	7066 {1.8}	11,552 {1.6}	21,792 {4.8}	33,670 {5.6}	61,901 {13.5} [9.8]
N Dakota	3150 {1.9}	4519 {0.6}	6509 {1.1}	17,251 {2.4}	44,830 {10.1}	46,248 {26.1} [15.1]

[1]Infections reported for selected US states that instituted early lock-downs (between March 21-22 2020) [49] [50] were divided by the population (in millions to one decimal point) according to the 2019 census [39]. [2]In {} are 7-day moving average deaths per million inhabitants [54]. [3]In addition, daily deaths per million inhabitants on 14 December is shown in [ ] for comparison [51]. [4]States that ordered residents to stay at home and the dates in which lock-downs come into effect were available [49] [50]. [5]Bold figures indicate deaths per million inhabitants increasing more than 4-fold from the preceding date in the Table. [6]The null hypothesis was tested by comparing the infections per million or death rate in both groups (with or without lock-downs) as described in the footnote of **Table 1**.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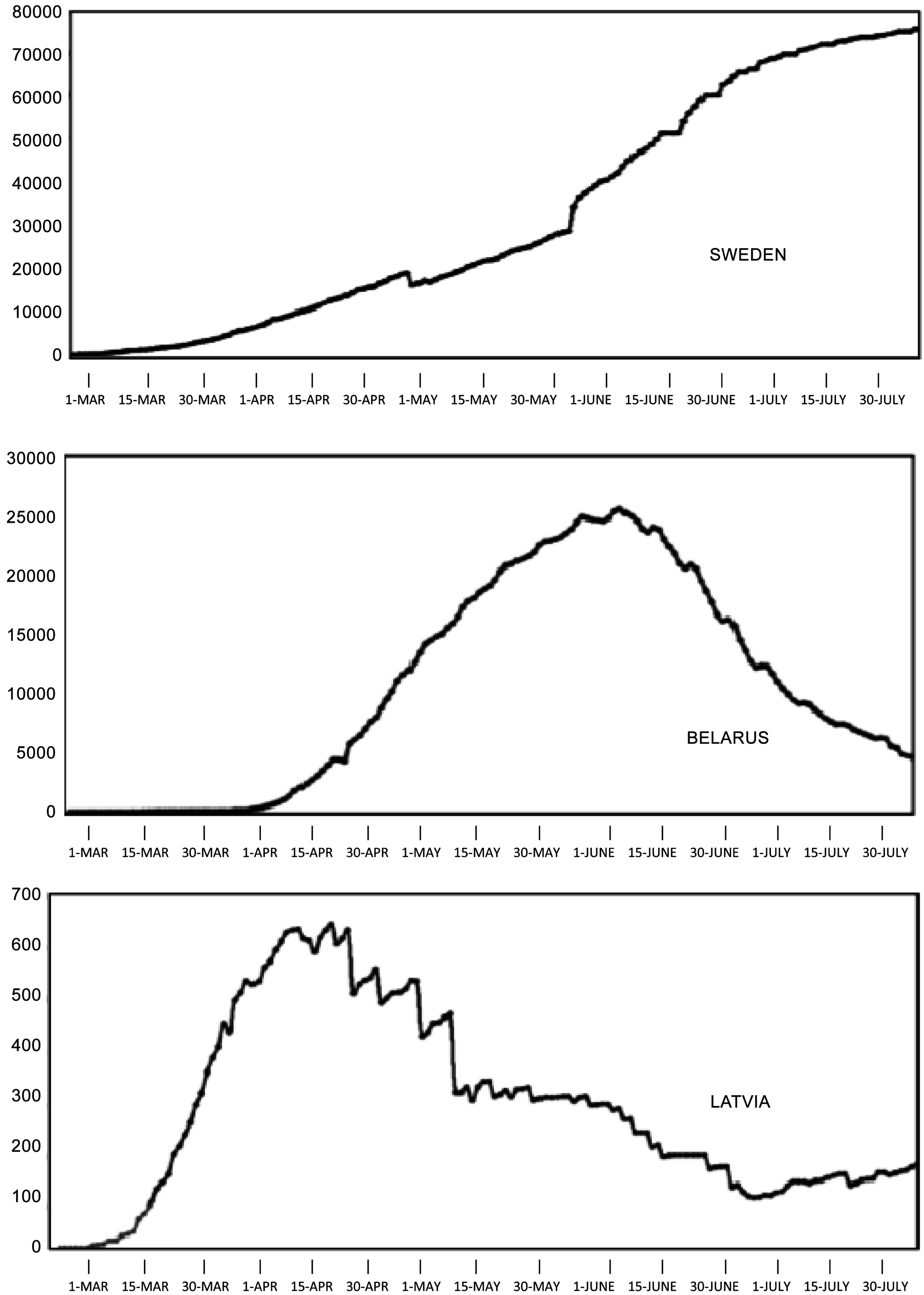
(a)



(b)

Figure 1. Number of active cases as a function of date from representative European countries listed in **Table 1**; (a) that mandated lock-downs and (b) that did not mandate lock-downs.

contrast, the European countries presented in Figure 1(b) [6] [56] that did not mandate lock-downs and allowed healthy people to remain outdoors [44] [45] do not show a bimodal curve of COVID-19 like those in Figure 1(a). Countries in Figure 1(a) show a bi-modal distribution with a first peak around mid-April 2020, and a valley either in mid-May, early May or mid-June in Spain, Greece and Slovakia, respectively while the number of active COVID-19 cases spike at the beginning of September 2020 in Spain, the middle of September in Greece, late September in France, UK, and Slovakia, and early October 2020 in Italy [6] (data not shown), demonstrating that lock-downs may have delayed but failed to prevent progression of COVID-19.

Not all European countries in Table 1(a) that mandated lock-downs show a bimodal curve within the period studied. Only Uruguay and Japan that did not mandate lock-downs show a bimodal progression for COVID-19.

Figures reported for at least 5 US states shown in Table 2 indicate that lock-downs did not prevent the spikes resulting in a four-fold increase in population mortality rate observed between 26 October and 14 December (in bold), when summer had ended and winter was approaching. Interestingly, most of the US states that instituted stay-home orders did so from 19 March (a week to ten days before the new infections peak). Stay-home orders were partially lifted by many U.S. states in early-mid May [50] during the valley of daily infections (data not shown). The lifting or relaxing of stay-home orders seems to precede and correlate with COVID-19 expansion suggesting that at best, lock-downs delay progression of the pandemic without an overall net benefit.

3.4. Mortality during COVID-19

Deaths per infections (×100) as well as per million inhabitants among countries in Table 1(a) with and Table 1(b) without-lock-downs fail to show a significant difference between the two groups of countries, demonstrating that lock-downs and stay-home orders do not affect the mortality of COVID-19. However, the infection mortality rates for COVID-19 (deaths over infections × 100) shown in Table 1 vary dramatically, ranging from less than 1% to over 14% and population mortality rates [deaths per million inhabitants] as late as 14 December range between 1 and 1100 among different countries [6].

Four fold increases in mortality per million inhabitants (bold in Table 1) occurred during the fall (October-December) in Greece and Slovakia as well as in Latvia and Lithuania. The data in Table 1 and Table 2 indicates that stay-at-home orders do not alter mortality figures.

As of July 21 there were in the world 17 countries with infection mortality rates at least 2-fold higher than the world average at that time (4.1%). From these countries, 9 were relatively small developing countries (4 of which are small islands) with health care difficult to assess. The remaining 8 countries with infection mortality rates higher than 8.2% included France (15.9%), Belgium (15.3%), UK (14.5%), Italy (14.3%), Hungary (13.7%), Netherlands (11.8%), Mexico (11.3%) and Spain (9.1%). All of these countries are located in the northern hemisphere where it was winter at the beginning of the pandemic. Only one of these, Mexico, did not mandate lock-downs of healthy individuals. Sweden that has been considered representative of "unlocked country" had an infection mortality rate of 7.7% (slightly inferior to the two-fold average of 8.2%). As of 7 September, 2020, Sweden's infection per million inhabitants as well as infection mortality rate remained considerably higher (8462, 6.7%) than its Scandinavian neighbors that instituted lock-downs (Norway 2098, 2.3% and Finland 1502, 4%). Although infection mortality rates had decreased in 26 October, Sweden's mortality rate remained higher (5.4%) than its neighbors (1.5% and 2.3% for Norway and Finland, respectively). However, these differences could diminish if adjusted by the chances of contagion related to population density (in people per km^2: 22 for Sweden versus 15 for both Norway and Finland) or to the crowding in their larger cities (with Stockholm nearly three times more populous than Oslo or Helsinki [39] [58]. The population mortality rate (deaths per million inhabitants) of Sweden (**Table 1(b)**) has trailed during 2020 behind countries like Spain, the UK and Italy that established early nationwide lock-downs (**Table 1(a)**).

In contrast with considerable increases observed in infections per million inhabitants, infection mortality rate in each country was relatively constant (**Table 1**). This observation suggests that the mortality resulting from COVID-19 is independent from seasonal sunlight and instead, large disparity of mortality for the same virus among different countries could correlate to variables yet to be elucidated (see Discussion). The infection mortality rate (deaths/infections × 100, as of 7 September, 2020) among every major developing country in South America (those countries shown in **Table 1** plus Colombia 3.2%, Brazil 3.1%, Paraguay 1.9%, and Venezuela 0.8%) was considerably lower than the infection mortality rate in several developed countries in Europe (see 8 European countries with highest infection mortality above). In contrast to infection mortality rates, the population mortality rate (deaths per million inhabitants) of the three Latin American countries in **Figure 1(a)** that instituted nation-wide lock-downs (Chile, Peru, and Argentina) compares to that of Spain, the UK, and Italy, and those rates are higher than the figures in Uruguay and Nicaragua (Latin American countries in the southern hemisphere that did not mandate lock-downs) (**Table 1(b)**).

4. Discussion

The presented data indicates that COVID-19 progressed differently in countries at northern latitudes as it was winter time and sun exposure was limited at the onset of the pandemic during December 2019-March 2020, than in countries in the southern latitudes where summer sunlight was abundant. The shift of highest infection rates from countries in the northern-towards countries in the southern-hemisphere reported in the present work correlates with seasonal variation in the flux of germicidal sunlight [31] [35] [37]. Together with the limited virucidal effect (within the ambient range) reported for temperature and humidity on SARS-CoV-2 [16] [24] (as well as previously established for influenza virus [25] [26] [27] [28] [29]), the most plausible explanation for the observed north-south and later south-north shift of infection is the role of virucidal sunlight in the progression of COVID-19 [35].

Predicting 7 billion infections and 40 million deaths in 2020 alone [7] suggests that current modeling of epidemics could be omitting a variable of importance in limiting the progression of viral pandemics [8] [59] [60]. The data presented here indicates that sunlight viral inactivation plays a role in the pandemic and it should not be ignored in modeling the evolution of infectious diseases. Considering the enormous number of infectious particles that can be broadcasted by an infected person [61] [62], even during the incubation period before symptoms can be detected (when molecular tests are still insensitive), the unavoidable contamination of environments indoor as well as outdoors must be considered (particularly in modeling) as a viral reservoir throughout the epidemic. This reservoir should be encompassed by a wide variety of contaminated natural and man-made surfaces and fomites, where SARS-CoV-2 can be inactivated relatively rapidly by summer sunlight (even in partial shade [63] [64]) or can persist with risk of infection for long periods at higher latitudes during winter or indoors most of the year [35].

In contrast, with considerable increases in infection per million inhabitants, relatively constant infection mortality rate in each country [between 29 May and 14 December, 2020 (**Table 1**)] suggest that the mortality resulting from COVID-19 infections is independent of seasonal sunlight and instead, mortality after infection should correlate with characteristics of the health system on each nation. COVID-19 infection mortality rates in developing countries of South America (11 of the largest countries) was considerably lower than in several (at least 8) developed European countries (see Results). Although perhaps counter-intuitive, this finding agrees with a previous report correlating higher COVID-19 mortality to higher national Gross Domestic Product (GDP) and explained as due to an older and more sedentary population in countries with higher GDP [65].

National differences in infection mortality rate (at times 4-fold or higher than the global average) produced by the same virus could result from a less efficient national health care system (due to lack of investment, training, or proper allocation of relevant resources). However, this notion seems at odds with the considerable differences in health expenditures, number of intensive care beds and number of ventilators between developed and developing countries [66] [67]. The extensive national health infrastructures made possible a considerably higher number of hospitalizations in developed European countries (with highest COVID-19 infection mortality during the first two quarters of 2020, see Results) than the number of hospitalizations in South American countries [66] [67]. It could be speculated that higher mortality rates after infection by the same virus could be the result of increased hospitalization, intubation, and other invasive procedures in developed countries, providing higher chances for nosocomial infections and deaths caused by germs commonly found in the hospital setting [68] [69] but reported as COVID-19 deaths during the crisis. This hypothesis seems reasonable since according to the European Center for Disease Control and Prevention, a total of 8.9 million healthcare-associated infections were estimated to occur each year without pandemics in European hospitals and long-term care facilities [70]. Thus, it can be speculated that higher rate of hospitalization (afforded by a large number of hospital beds, respirators and infrastructure) of patients weakened by COVID-19 could be followed by nosocomial infections leading to death at the higher frequency observed in European developed countries (see **Table 1**). The apparent and puzzling differential mortality between developed and developing countries during early stages of the pandemic demands extensive elucidation by post-mortem and other forensic studies but these are unlike, at least during the ongoing crisis.

In any case, the findings on COVID-19 mortality highlight the need for increased awareness on the efficient disinfection of material employed in intubation, respirators, bronchoscopes and overall environmental sanitation of hospitals [68] [69] during the pandemic, and especially during winter [31] [35].

Less definitive should be considered a correlation between lock-downs and a bimodal progression of COVID-19. However, the curves shown for at least some European countries (**Figure 1(a)**) early in the pandemic suggest that mandating individuals to remain indoors may have altered the natural progression of COVID-19, at least during the early (and crucial) stages.

The present study was initiated under the assumption that early nationwide stay-at-home orders or lock-downs would impair the time people spent outdoors, reducing or masking altogether any seasonal effect of sunlight on the pandemic. Thus, epidemiological figures from "locked countries" would have served as an adequate negative control data set in the seasonal study reported here. In contrast, any seasonal effect should be evident by comparing to data from the countries and US states that did not impose stay-at-home orders. Unexpectedly, initial comparison of epidemiological data (during May 2020) from a limited but illustrative set of countries that had mandated early the most restrictive lock-down measures and those that did not order healthy citizens to remain at home failed to show the expected epidemiological differences, promoting further the present study.

It has been predicted by computer modeling that millions of deaths were averted by lock-downs [71] [72]. The hypothetical benefit of drastic curfews, quarantines, stay-at-home orders and lock-downs may sound reasonable but if true, then, there should have been a statistically significant difference between the infection rate and/or death rate in countries that established quarantine and lock-downs versus countries that did not mandate lock-downs. Although not every country in the world and state of the USA is discussed in the present study, the countries considered (24 countries analyzed in **Table 1** plus 13 additional countries addressed in the text of Results, plus 8 US states) should be enough to detect significant differences resulting from quarantines and lock-downs if significant differences should exist.

To justify the high cost of lock-downs, any positive effect should have clearly (and statistically) surfaced in the present study above any potential effect of co-founding variables (curfew compliance, mask wearing, obesity, urbanization of US states, demographics, etc.). Any limitations assigned to the accuracy of the data reported by different countries or US states should affect equally both data sets (with and without lock-downs), thus having little bearing on the conclusions being presented.

The lack of an effect of lock-downs on COVID-19 presented here agrees with previous studies using virtual simulation, as well as analysis of epidemiological data. Lock-downs and other restrictive measures remained in place in many countries throughout the year (2020) in spite of reports indicating as early as July-August 2020 that 1) infection rates and mortality rates of COVID-19 fell among countries with and without lock-downs without a significant pattern [8]; 2) lock-downs preventing healthy individuals from remaining outdoors had not resulted in significant difference in infection rates when compared to countries where individuals were free to remain outdoor [35]; and 3) full lock-downs were not associated with statistically significant reductions in the number of critical cases or overall mortality [73]. In addition, there have been a number of studies published during the last quarter of 2020 indicating that lock-downs or variable degrees of stay-at-home requirements were not statistically linked to nor significant predictors of—mortality, deaths per million or case fatality rate [24] [45] [65]. Moreover, any benefits of lock-downs were questioned in Germany [74], not apparent in the Rep. of South Africa [75], and ruled out as responsible in any decrease of the effective epidemic reproductive rate in the UK, suggesting these authors that key predictions by computer simulation should be considered artifacts [76]. These previous findings and the present report demonstrate by different and independent approaches that lock downs were both superfluous (did not prevent the explosive spread of COVID-19) and ineffective (did not slow down the death growth rate), affirming that virtual simulation of epidemics could complement but never replace actual epidemiological data and well established microbiological principles in policy making. The fact that the rather simple and straightforward approach employed here (key data in two sets of countries followed through most of the year) failed to detect any benefit in COVID-19 infection or mortality in countries that instituted nation-wide lock-downs should be convincing evidence, or at least rise concerns, about insisting during 2021 in mandating of costly but ineffective restrictive measures. Considering the devastating effect on society and the economy, the burden of proof should fall heavily on proving a benefit of lock-downs and not with demonstrating their irrelevance.

Quarantine and other restrictive confining measures may have worsened the prospects of certain countries, particularly of those in the southern hemisphere that rushed to emulate the policies taken by countries in the northern hemisphere without considering the seasonal difference. Quarantine in the southern hemisphere was implemented in several countries during early 2020, summer time there, where the sun at full virucidal potential could have reduced the progression of the epidemic by naturally reducing the infectious viral load in the environment [35] broadcasted by the then relatively low number of cases in these countries [6]. Later (in July 2020) several of these southern hemispheric countries still implementing strict quarantines (see **Table 1**) entered winter with a considerable population of susceptible individuals that, when eventually released from quarantine, could fuel COVID-19. However, at this time, countries in the southern hemisphere did not have intense sunlight to rapidly inactivate the virus in contaminated environments [35] thus accounting for the relatively large increase in infections (bold figures in **Table 1**).

The data presented herein indicates at least three potential factors that could increase the number of COVID-19 infections. The most obvious is a seasonal component in the pandemic negatively correlated to local solar flux. This component demonstrates that virus infectious in the environment plays a role in the pandemic since direct person-to-person transmission should be relatively independent of solar inactivation (affording not enough time to inactivate the virus). A second factor can be identified among some countries where an increase in infections (and mortality) occurred even after stay-at-home orders, lock-downs, and other stringent confining measures had been in place. This increase could be related to confining people indoors, at home or in nursing homes, thus increasing (or assuring) contagion among individuals under the same roof. Lastly, spikes of COVID-19 can be detected after stay-home sanctions are lifted. Like wildfires feeding off dry timber and hurricanes hot moist air, epidemics need susceptible individuals to persist and progress. The end of quarantines could fuel COVID-19 spikes when a considerable population of susceptible individuals kept locked in their homes, (thus deprived of sunlight, lowered their levels of vitamin D, and weakened their immune competence by staying long periods indoor [77] [78]) are eventually released, therefore increasing the chances for COVID-19 to flash up. This possibility seems supported by previous data indicating that lock-down in Argentina (among the longest and more strict in the world, requiring official transit permits strictly enforced by police) only postponed infections by hindering mobility without a net benefit [57]. Strict curfews and lock-downs did not prevent Argentina from increasing 4-fold its mortality rate twice (from May to September) as shown in **Table 1(a)** (in bold).

We can envision the progression of the epidemic (in absence of vaccination or other pharmaceutical interventions) as the result of the interaction and mutual balance of at least four main factors (some counteracting each other). The first involves the virulence and contagiousness of the germ, being relatively slow but progressively attenuated by multiple passages through healthy immune-competent hosts (this viral passage and natural attenuation should be delayed by stay-at-home orders, wearing face masks, and keeping social distancing). Secondly, virulence of the germ is more or less countered by the higher or lesser capability of the human host in mounting an efficient immune-response. The human host sensitivity to infection fluctuating with the patient general health, nutrition, metabolic condition (including levels of active vitamin D), expression of relevant genes, and psychological outlook of each individual during the crisis [77] [78]. Third, throughout the epidemic, a considerable virus load is broadcasted by infected patients (even asymptomatic) into the environment, contaminating a variety of surfaces. Lastly, fourth, in the absence of sunlight (during winter in many temperate zones and indoors), the reservoir of virus in contaminated environments persist with risk of infectious for considerable periods of time. In contrast, when sunlight is abundant, viral inactivation proceeds rather quickly outdoors and at slower rate even in the shade [31] [35] [37] [63] [64].

5. Conclusion

The differential increase in infections per million inhabitants between countries in the northern versus the southern hemisphere indicates a seasonal component in the progression of COVID-19. This seasonal progression indicates that an environmental component plays a relevant role in the pandemic. In contrast, mortality rate for the same virus among different countries did not show a seasonal component and instead, it was relatively characteristic for each country. When lock-downs are eventually lifted, susceptible individuals exposed to virus persisting in the environment could fuel new spikes of infection. Similar epidemiological data amongst "locked" and "unlocked" countries presented in this study demonstrate that measures intended to restrict mobility confining populations indoors had no effect on the chances of healthy individuals becoming infected with SARS-CoV-2, or dying of COVID-19, thus failing in preventing, or significantly reducing, the spread or mortality of the pandemic as such policies intended.

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Author Contribution

The single author (Dr. Jose-Luis Sagripanti) is solely responsible for the content of the article.

Data Availability Statement

The epidemiological data employed in this study is freely available from the sources listed in References. Most reprints of the listed References can be downloaded from the world wide web. Those articles not freely available can be requested from the author.

Animal and Human Experiments

No experiments utilizing animals or humans were undertaken in this study.

Conflicts of Interest

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The author (Dr. Jose-Luis Sagripanti) is not associated to any industrial or commercial enterprise. The author is not associated to any political party, serving for 30 years under various governments with different political orientations. No political issues were considered during the study presented here and the findings should not be construed as supporting or criticizing any party or particular government.

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