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COVID-19: Monitoring the propagation of the first waves of the pandemic

William Knafo*

Laboratoire National des Champs Magnétiques Intenses, CNRS-UPS-INSA-UGA, 143 Avenue de Rangueil, 31400 Toulouse, France

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Abstract – *Introduction*: A phenomenological approach is proposed to monitor the propagation of the first waves of the COVID-19 pandemic.
Method: A large set of data collected during the first months of 2020 is compiled into a series of semi-logarithmic plots, for a selection of 32 countries from the five continents.
Results: Three regimes are identified in the propagation of an epidemic wave: a pre-epidemic regime 1, an exponential-growth regime 2, and a resorption regime 3. A two-parameters scaling of the first-wave death variation reported in China is used to fit the first-wave data reported in other countries. Comparison is made between the propagation of the pandemic in different countries, which are classified into four groups, from Group A where the pandemic first waves were contained efficiently, to Group D where the pandemic first waves widely spread. All Asian countries considered here, where fast and efficient measures have been applied, are in Group A. Group D is composed of Western-European countries and the United States of America (USA), where late decisions and confused political communication (pandemic seriousness, protection masks, herd immunity, etc.) led to a large number of deaths.
Discussion: The threat of resurging epidemic waves following a lift of lockdown measures is discussed. The results obtained in Asian countries from group A, as Hong Kong and South Korea, are highlighted, and the measures taken there are presented as examples that other countries may follow.

Keywords: Asia, Australia, Belgium, Brazil, Czech Republic, China, COVID-19, Epidemic, Epidemic wave, Epidemiology, Europe, France, Germany, Greece, Hong Kong, Immunity, India, Iran, Israel, Italy, Japan, Lockdown, Mexico, Morbidity, Morocco, Mortality, The Netherlands, Nigeria, Norway, Pandemic, Phenomenological Description, Philippines, Portugal, Protection, Resurging Epidemic Waves, Russia, Sars-CoV-2, Sepsis, Singapore, South Korea, Scandinavia, Spain, South Africa, Sweden, Switzerland, Taiwan, Western Europe, United Kingdom, USA, Virus

Introduction

In the first months of 2020, the first waves of the pandemic spread of the coronavirus disease 2019 (COVID-19) have affected most of the countries worldwide [1]. This disease, caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), was first reported in end 2019 in Hubei province, China [2, 3]. At the time of writing this paper (9 May 2020), almost 300,000 deaths have been reported and multiple challenges have emerged: slowing down the spread of the virus, offering adapted medical care, saving lives, developing a vaccine to immunize the population, and anticipating a forthcoming economic crisis. As a first step, slowing down the pandemic propagation is essential to limiting the number of deaths occurring in a few-weeks timescale and, thus, to avoid a cascade of related issues. Without this, an uncontrolled exponential propagation could lead to cumulative death tolls of up to one or even a few percent of the population. This corresponds to a situation where herd immunity would be achieved in a "natural" manner [4–6].

The target to avoid such a dire situation offers a rare case where scientists can directly guide politicians and where their recommendations on short- and medium-term decisions can have enormous impacts for the community/country. They can monitor the pandemic statistics, they can model it, they can propose solutions to slow down the pandemic propagation, they can follow or anticipate the impacts of given series of political decisions. In recent weeks, several epidemiological models and reports emerged [7–15], some of them having impact in national press and immediate consequences on political decisions. In addition to the work from epidemiologists, modelling and graphical tools have been proposed by physicists (see for instance [16–19]). In particular,

*Corresponding author: william.knafo@lncmi.cnrs.fr

phenomenological approaches, such as that proposed in this work, are suited to monitor the propagation of a pandemic.

Here, a battery of semi-logarithmic plots on the propagation of the COVID-19 pandemic is given, for a selection of 32 countries from the different continents. The choice to consider full-country data (rather than comparing territories of similar populations) is motivated by the fact that political decisions are generally taken at a national scale. A two-parameter scaling of the death data reported in China is used to fit the first waves of the epidemic in a selection of countries, where the spread was well-advanced in beginning of May 2020 (USA, Spain, Italy, United Kingdom [UK], France and Germany). The graphs constitute simple tools to identify trends and key moments in the propagation of the pandemic in a country. They offer an easy way to assess and compare the efficiency of measures. The success of those taken in Asian countries is emphasized. The situation in several Western Europe countries and in the USA is opposite. Confused political communication about the appreciation of the pandemic' seriousness [20, 21], recommendations to wear protection masks [22], and the consequences of a herd immunity scenario [23], has been observed. In these countries, the delay in the application of strong containment measures led to tens of thousands of deaths after the first waves of the epidemic. An early lift of the lockdown may also lead to the resurgence of further waves of the epidemic. The monitoring tools compiled here, once updated, will help in forecasting resurging waves of the pandemic. The fatality rate and the question of achieving herd immunity, as well as the exponential consequences of a delay or inefficiency in the application of measures are discussed.

Materials and methods

Data presented here were extracted from the Johns Hopkins University [24], Santé Publique France [25] and "https://dashboard.covid19.data.gouv.fr" databases. They were accessed on 9 May 2020 and correspond to confirmed cases and deaths reported in 32 countries up to 8 May 2020 (most of the data were extracted from [24], some French data were completed from [25], and French confirmed cases data were extracted from "https://dashboard.covid19.data.gouv.fr"). This selection is composed of the first countries hit by the pandemic in Asia and western countries, and of a panel of lately-hit countries from the different continents. Discussion about possible errors in some official tolls would go beyond the scope of this paper and is not made here. Delays in the report of data (for instance during weekends) sometimes lead to an additional noise in the graphs, but they weakly affect the general trends observed on several-week time scales.

Data are presented in a systematic and progressive way. Plots of raw data, i.e., cumulative reported cases and death numbers versus time, are first considered. Daily deaths numbers are then presented. For all sets of data, a "shifted" time is adjusted so that day $D = 0$ corresponds to the extrapolation of the exponential-growth regime to $N = 1$ cumulative death. All data are then normalized with regard to their population, and deaths numbers are given per 100,000 inhabitants. In these last graphs, a second "shifted" time is used, and the day $d = 0$ is defined as the extrapolation of the exponential-growth regime to $n = 0.001$ cumulative deaths/100,000 inhabitants.

For a selection of countries, the evolution of the cumulative death toll is fitted using one or two single-wave contribution derived from a smoothed curve constructed from the Chinese cumulative single-wave death variation. It is assumed that, for each epidemic wave, the exponential-growth and decay regimes are similar to those reported for the first epidemic wave reported in China. For each wave, two parameters, an offset in time and a scaling factor in the death number, are adjusted to reproduce both cumulative and daily death variations. A factor F is also defined as the ratio of cumulative deaths at the beginning of the lockdown start and at the end of the epidemic wave.

The countries considered here are classified in a four-group scheme (Groups A–D), depending on the degree of spread of the pandemic in their population on 8 May 2020.

Results

Spread of the pandemic in a selection of Asian and Western countries

Figure 1 presents the time variation of confirmed case and death tolls from a selection of six countries early hit by the COVID-19 pandemic, on a time window covering fully or partly the first epidemic waves. Figures 1a, 1c, and 1f show the evolution from 1 January to 8 May 2020 of the cumulative confirmed cases, cumulative deaths, and daily deaths in China, South Korea, Italy, Spain, France (mainland) and the USA. Time offsets between the variations from the different countries result from the delayed arrivals of the virus on their territory.

China was the first country to be hit by the pandemic, where the first wave ended in late April 2020, with cumulative confirmed cases saturating at ≈ 80,000 and cumulated deaths saturating < 5000 (initial saturation to ≈ 3300 deaths corrected to ≈ 4600 on 17 April 2020). South Korea was hit a few weeks after China and was less affected than the other countries considered here, with < 11,000 cumulative confirmed cases and < 300 cumulative deaths in the beginning of May 2020. The USA was the last country of this selection to be hit, but it was the most affected with > 1,000,000 cumulative confirmed cases and > 70,000 cumulative deaths in the beginning of May 2020. The three Western European countries were hit a few days after South Korea and were strongly affected, with ≈ 200,000 cumulative confirmed cases and ≈ 30,000 cumulated deaths in each country in the beginning of May 2020. These graphs show that, when the epidemic is active in a country, the number of cumulative deaths increases in an exponential manner, which leads to a linear increase in the semi-logarithmic scale of the graphs.

Complementarily graphs are shown in the panels (b, d, f) of Figure 1 where the cumulative confirmed cases, cumulative deaths and daily deaths are plotted as a function of a

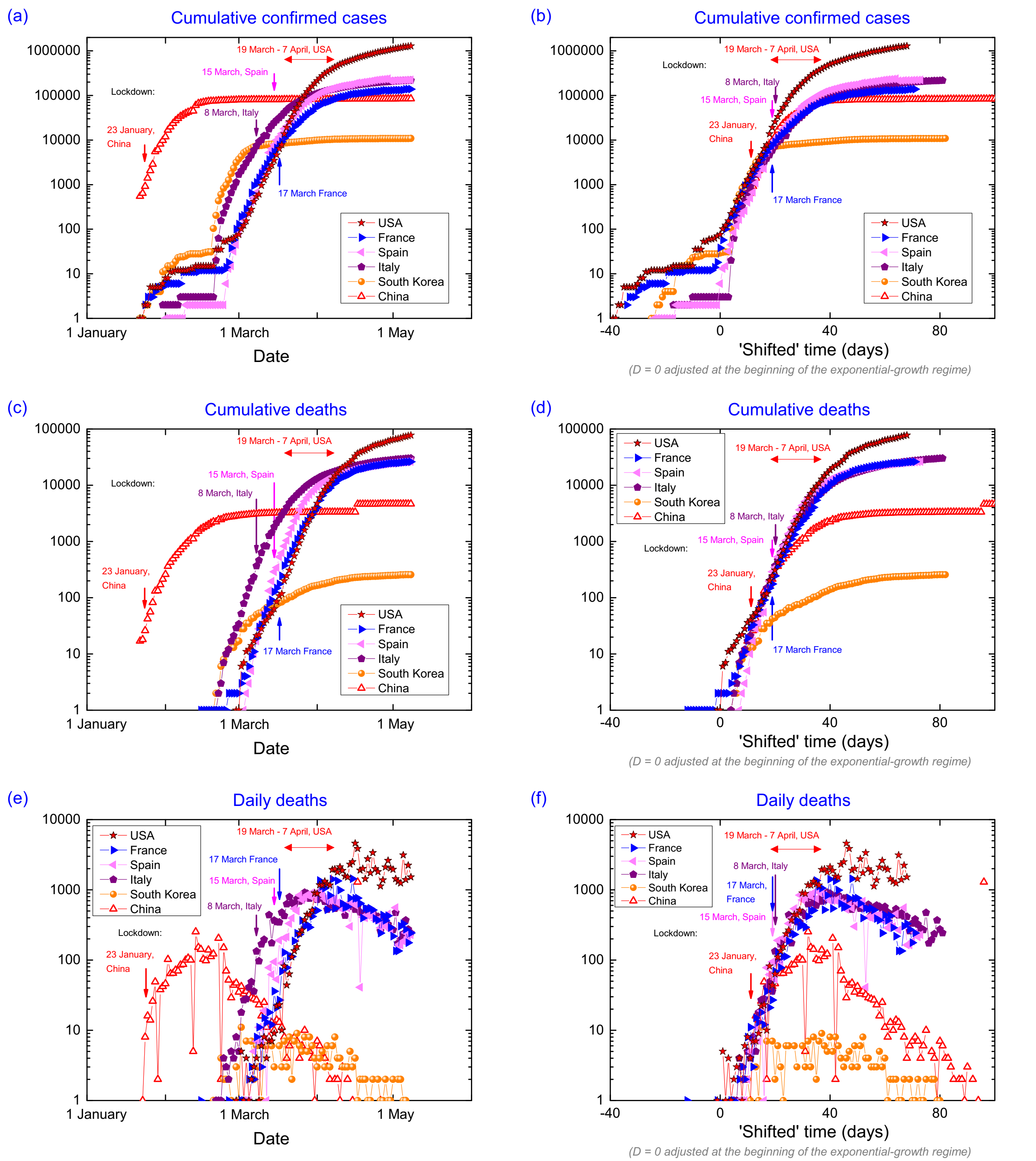

Figure 1. Focus on six countries: China, South Korea, Italy, Spain, France (mainland) and the USA [27–31]. Plots of cumulative confirmed cases (a) versus date and (b) versus "shifted" time, of cumulative deaths (c) versus date and (d) versus "shifted" time, and of daily deaths (e) versus date and (f) versus "shifted" time.

"shifted" time. For each country, the "shifted" time is adjusted so that day $D = 0$ corresponds to the extrapolation to a number $N = 1$ of the exponential increase of cumulative deaths. A deviation from the exponential regime is observed in all countries a few days or weeks after $D = 0$. An epidemic peak corresponding to a several-week plateau in the time variation of the daily death number is visible for the six countries considered in Figure 1. This plateau was always

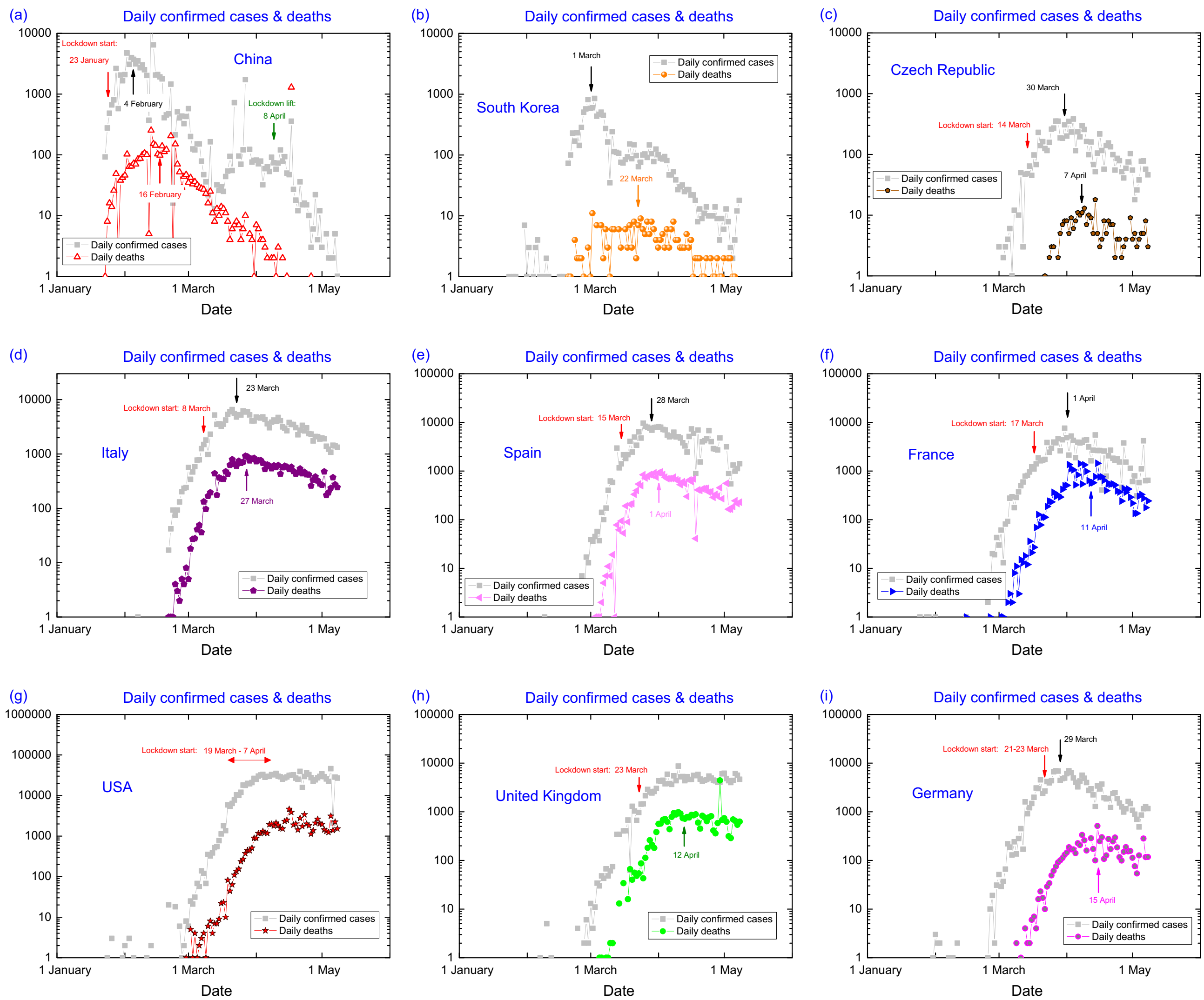

Figure 2. Time variation of daily confirmed cases and deaths in a selection of nine countries: (a) China, (b) South Korea, (c) Czech Republic, (d) Italy, (e) Spain, (f) France, (g) USA, (h) UK, and (i) Germany [27–35].

maintained to < 10 daily deaths in South Korea. It reached 100–200 daily deaths in China, 500–1000 daily deaths in the four considered Western Europe countries, and a maximum of 2000–4000 daily deaths in the USA.

Figure S1 in the Supplementary Materials generalizes the graphs from Figure 1 to a total of 32 countries worldwide. It confirms that all countries follow similar trajectories. A large scattering of the data is visible in the plots of the cumulative confirmed cases as a function of the "shifted" time (Fig. S1c). In contrast, the cumulative deaths plotted as a function of the "shifted" time almost converge on a unique line in the exponential regime of the pandemic propagation (Fig. S1f). This difference can be explained as the number of cumulative confirmed cases is a less reliable quantity than the number of cumulated deaths, for the following reasons:

→ The tests on the population are done with different financial resources, with different efforts, and different constancies, depending on the considered country. A large proportion of cases are not detected. Also, the testing procedure often focuses on people suspected to be infected.

→ When the number of cases increases, it becomes more difficult to detect all of them. Even in the countries equipped with the best detecting system, detection is less efficient when it approaches its maximal capacity (saturation of a detector).

In the next Sections, the number of deaths, thought to be more reliable, will be considered preferentially. We note that voluntary or involuntary failures in death counting can also occur. This was for instance the case in France, where incomplete numbers of deaths (only deaths in hospitals) were communicated before 1 April 2020. In the UK, the deaths outside hospitals were also not counted before 29 April 2020. In many countries, only the deaths in hospitals have been counted so far.

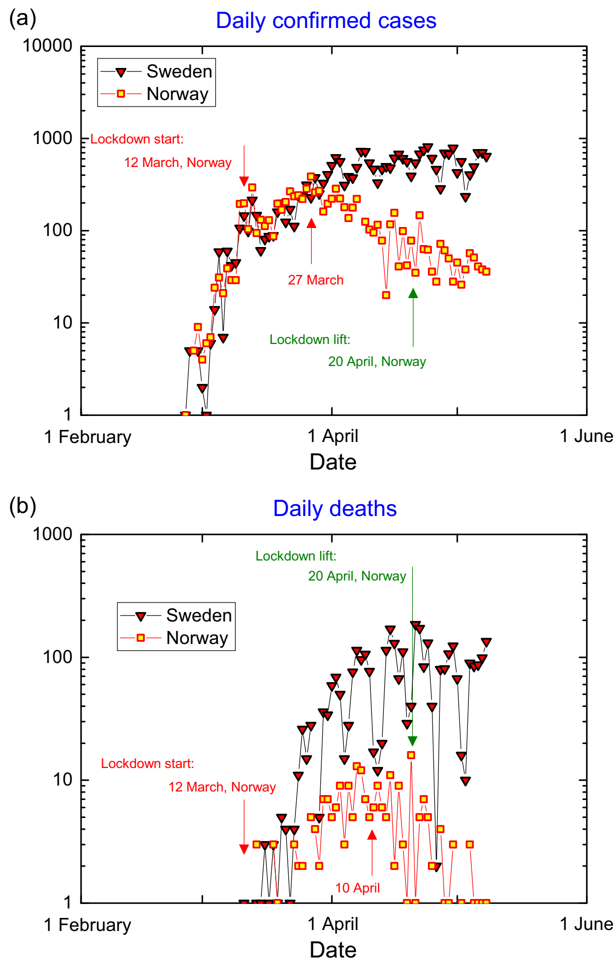

Figure 3. Comparison of daily (a) confirmed cases and (b) deaths in Sweden and Norway [36, 37].

Complementarily to Figure 1, Figure 2 presents a comparison, for a selection of nine countries in Asia and Western North hemisphere, of the variation with time of the daily confirmed cases and death tolls. For each country, the variation of the daily death number follows that of the daily confirmed cases, with a delay of 5–10 days. In China, a significant decrease of daily confirmed cases was observed 10 days after the setup of lockdown [30], and the epidemic peak in the number of daily deaths was observed 10 days later. After this peak, the number of daily deaths has decreased within an exponential decay, as indicated by the negative-slope linear variation in the semi-logarithmic scale of the graphs. Two months later, lockdown was lifted on 8 April [31]. At this date, there were a few daily deaths and $\approx$ 50–100 daily confirmed cases in China. The case of South Korea is unique: after an early increase of daily confirmed cases, this number reached a maximum of $\approx$ 1000 before strongly decreasing. By the end of April, less than 2 daily deaths and $\approx$ 10 daily confirmed cases were reported. Before May, the number of daily deaths has always been contained to less than 10 in South Korea.

In the Czech Republic, Italy, Spain, France, and Germany, the epidemic peak has been observed for both numbers of daily cumulative cases and deaths. However, in Italy a few weeks after the peak the number of daily deaths decreased at a slower rate than in China. In the USA and in the UK, both daily confirmed cases and death tolls have been saturating in the last weeks of April, and no clear peak emerged so far from the plateaus. In all of these western countries (except the Czech Republic), daily confirmed cases and death numbers are still several orders of magnitude higher than those in China when lockdown was lifted [31], or than those in South Korea after the epidemic peak.

Figure 3 focuses on a comparison between two neighbors from the Scandinavian Peninsula: Sweden and Norway. Beyond their geographic and climatic similarities, both countries are quite comparable in term of population and density (10 million inhabitants and 450,000 km^2 for Sweden, 5.4 million inhabitants and 385,000 km^2 for Norway [37]). The pandemic started in these two territories almost simultaneously, as shown by the sudden increase of daily confirmed cases after 1 March (Fig. 3a) and of the daily deaths (Fig. 3b) two weeks later in both countries. Two opposite strategies were followed by Sweden and Norway to face the pandemic. Sweden was guided by the target to let the pandemic spread over the territory, so that herd immunity [4–6] is achieved in a "natural" manner [38]. A few days after the first reported cases, Norway applied strong measures and lockdown was set on 12 March [35], i.e., before the first reported death. The effects of these measures are visible in Figure 3, with broad maxima centered on 27 March in the daily cumulative cases, and on 10 April in the daily deaths. In the beginning of May, the first epidemic wave almost ended in Norway, with < 1 "average" daily deaths and < 30 daily confirmed cases. In Sweden, without lockdown the number of daily reported cases and deaths increased before reaching a plateau with 300–900 daily confirmed cases and 10–200 daily deaths. A large noise in the data indicates a difficulty to collect data in this country. In the beginning of May 2020, $\approx$ 200 cumulative deaths were reported in Norway and $>$ 3000 cumulative deaths were reported in Sweden, where the first epidemic wave was about to continue and to lead to a higher death toll. The comparison between Sweden and Norway is a direct illustration of the human cost of a herd immunity strategy.

Phenomenological description

Definition of three epidemic regimes

Figure 4 focuses on the variation of cumulated death and daily death tolls normalized per 100,000 inhabitants for four countries: China, South Korea, Italy and France. In the non-normalized graphs plotted in Figures 1b, 1d, 1f, the date corresponding to the day $D = 0$ of the "shifted" time scale was defined by adjusting the extrapolation of the exponential-growth regime to $N = 1$ cumulative death. Since the criterion $N = 1$ is not proportional to the population, if we compare two countries of different populations and hit at the same time by the pandemic, a later "shifted"

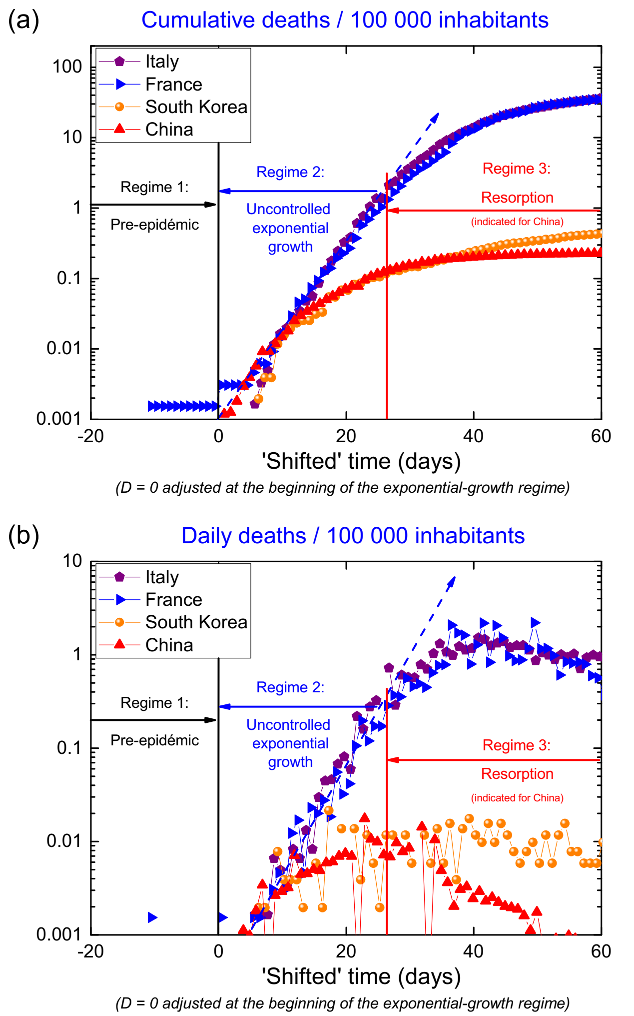

Figure 4. Identification of three regimes in a single-wave epidemic propagation, illustrated with their signatures in the variation of (a) cumulative deaths/100,000 inhabitants and (b) daily deaths/100,000 inhabitants of Italy, France, South Korea, and China.

date D is artificially defined for the country of smaller population. The consideration of data normalized with regard to the population permits one to avoid this artefact. In Figure 4, but also in the next graphs presenting tolls normalized per 100,000 inhabitants, the day $d = 0$ is defined as the extrapolation of the exponential-growth regime to $n = 0.001$ cumulative deaths/100,000 inhabitants. Normalized death tolls will be systematically considered in Section "Comparison of the propagation of the pandemic for a selection of countries".

Figure 4 indicates that three regimes can be identified in a single-wave propagation of the pandemic:

→ Regime 1: pre-epidemic phase.
- ○ Zero or a few isolated cases are reported, and the propagation rhythm is zero or weak. In this regime, the epidemic is kept at bay.

→ Regime 2: exponential- and uncontrolled-growth phase.
- ○ The propagation is wild and not slowed down. Cumulative, but also daily, confirmed cases and deaths are increasing exponentially, and a universal law is followed. In the semi-logarithmic-scale graphs presented here, all countries show a linear variation of similar slope when they are in regime 2.

→ Regime 3: resorption phase.
- ○ After a deviation from the exponential-growth regime 2, this phase corresponds to a decay of the epidemic propagation. Here, we define the transition (in fact a broad crossover) from regime 2 to regime 3 at the date when the numbers of daily death tolls passes through a maximum, which is identified as the epidemic peak. The decline of the epidemic propagation ends asymptotically by a saturation of the cumulative death number. Regime 3 can be the result of several causes:
  - the success of a national policy in the slowing down of the virus propagation (mitigation, containment, lock-down, vaccination, etc.),
  - a number of contaminated cases approaching the total population, which was not immunized before the epidemic (if there is fewer persons to contaminate, there will be less infected people), meaning that herd immunity is approaching,
  - particular local conditions (weather, human density, age, obesity in the population) unfavorable to the virus, or
  - a failure (voluntary or not) in the counting system.

While the transition between regimes 1 and 2 is sharp and fast, that between regimes 2 and 3 is progressive and spreads over several weeks. Successive waves can also occur on a given territory, leading to a more complex variation of the death number than that presented here for a single wave.

Two-parameters description of first-epidemic waves

A universal behavior is observed in regime 2 where the epidemic dynamics is out of control. An open question is whether the transition between the regimes 2 and 3 is also universal, or if it depends on local specificities, as an interaction rate in the population, the efficiency of social distancing, mitigation, containment or lockdown when applied. Here, extrapolations are made with the crude, but perhaps not unrealistic, assumption that for each epidemic wave the transition between regimes 2 and 3, and then the resorption in regime 3, are similar to those reported for the first epidemic wave in China. The evolutions of the cumulative death tolls in several countries are estimated using a single-wave smoothed curve constructed from the Chinese cumulative death variation, or using the superposition of two successive waves. For most of the countries considered at this stage (data up to 8 May 2020) the assumption of a unique epidemic wave is proposed to fit the data within a first approximation. Higher final numbers than those given

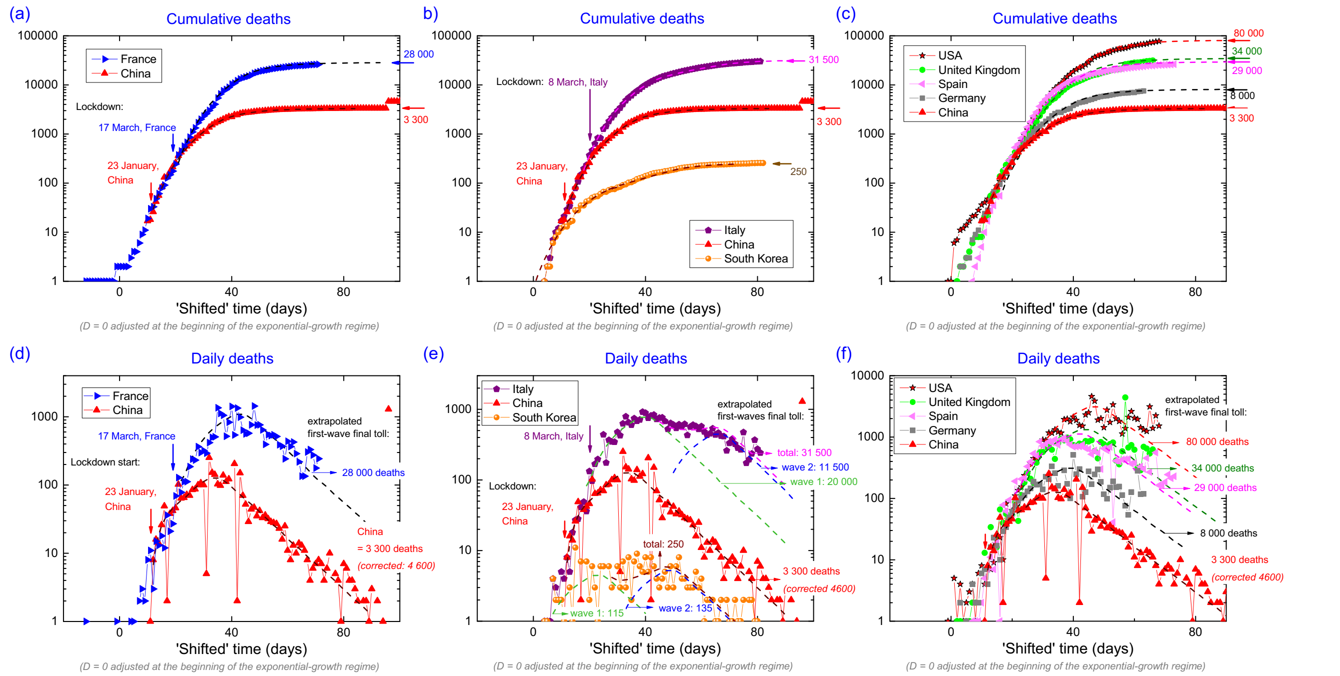

Figure 5. Extrapolation of (a) cumulative and (d) daily death numbers in France, assuming a unique wave similar to that reported in China. Extrapolation of (b) cumulative and (e) daily death numbers in Italy and South Korea, assuming two successive epidemic waves, each one being similar that reported in China. Extrapolation of (c) cumulative and (f) daily death numbers in the USA, UK, Spain and Germany, assuming a unique wave similar to that reported in China.

here can be reached later, if deviations from a single-wave behavior are induced by less-efficient lockdown measures, resurging waves or late death-toll corrections. A long plateau instead of a sharp epidemic peak can be the signature of less-efficient or hasty-lifted lockdown measures.

For each wave, two parameters, an offset in time and a scaling factor in the death number, are adjusted to reproduce both cumulative and daily death variations. A factor F is also defined as the ratio of cumulative deaths at the beginning of the lockdown and at the end of the epidemic wave. Efficient lockdown measures are associated with a smaller value of F.

Graphically, in a semi-logarithmic scale this corresponds to a translation of the dashed black line initially adjusted on China's data. These fits summarized in Figure 5 do not intend to precisely predict the final number of cumulative deaths for an on-going epidemic wave. They show that, within a first approximation, the dynamics of a COVID-19 wave is similar in the different countries, and they indicate the typical time scales and the orders of magnitude of the final death tolls expected at the end of an epidemic wave.

For France, the best fit to the data, with a factor $F = 160$, corresponds to a final number of 28,000 cumulative deaths for the first wave. Fits are compatible with extrapolations for the first wave to 8000 final cumulative deaths in Germany ($F = 80$), 29,000 final cumulative in Spain ($F = 100$), 34,000 final cumulative deaths in the UK ($F = 100$), and 80,000 final cumulative deaths in the USA (F cannot be estimated due to different lockdown dates in the different states). Long plateaus in the USA and UK data suggest that a single wave contribution, scaled from the Chinese first-wave data, might not be sufficient to fit the data, and that higher final tolls may be expected. For Italy and South Korea two successive waves are used to describe a long epidemic plateau. For Italy, the fit is compatible with a first wave of 20,000 final cumulative deaths, with a maximum peaked 40 days after the start of regime 2, and a second wave of 11,500 final cumulative deaths, with a maximum peaked 60 days after the start of regime 2. For South Korea, the fit is compatible with a first wave of 115 final cumulative deaths, with a maximum peaked 20 days after the start of regime 2, and a second wave of 135 final cumulative deaths, with a maximum peaked 50 days after the start of regime 2. The results from these phenomenological fits are in good agreement with those from more sophisticated models (see for instance [15]).

Figure 6 summarizes the fits made here for the USA, UK, Spain, Italy, France, and Germany. In this graph, the daily death tolls are plotted as function of non-shifted date. Two months after an epidemic peak of 100–200 daily deaths, China ended the lockdown in Wuhan, where the virus has been the most active, on 8 April [31]. At this date, the daily death number was of the order of 1. An almost-constant negative slope in the evolution of the daily death numbers, in this semi-logarithmic plot, was reported during the two months after the epidemic peak in China. It indicates an exponential decay of the daily death number with time. Assuming a similar decay for the other countries,

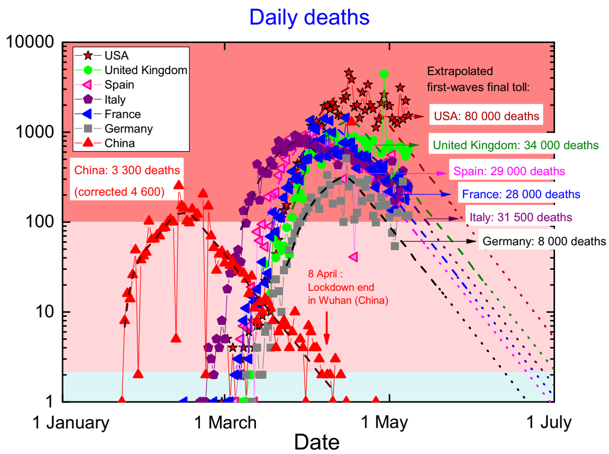

Figure 6. Fit to the daily death tolls as function of date in the USA, the United Kingdom, Spain, France, Italy and Germany, assuming epidemic waves dynamics similar to that reported in China.

longer lockdown duration is expected in countries where the epidemic peak reached a higher level. However, contrary to the Chinese strategy, in beginning of May 2020 most of the Western countries were planning to lift their lockdown measures soon after the epidemic peaked, at a date where hundreds of daily deaths were still being reported (see for instance [39]).

Comparison of the propagation of the pandemic for a selection of countries

While the raw data presented in Section "Spread of the pandemic in a selection of Asian and Western countries" spotlight the countries with a large population, in this section we consider graphs where the cumulative and daily death tolls have been normalized with regard to the population [37] (see Sect. "Definition of three epidemic regimes"). This permits to quantitatively compare the spread of the pandemic in countries of different populations.

Figure 7 presents the cumulative and daily death tolls normalized per 100,000 inhabitants as function of a "shifted" time, for a selection of 32 countries worldwide (data ending in the beginning of May 2020). Complementary plots of confirmed cases and deaths data for these countries are presented in the Supplementary Materials (Fig. S1). In most of the countries, a similar exponential-growth regime is observed in the time-evolution of the death numbers.

The efficiency of the measures taken in Asia is revealed spectacularly in the graphs of Figure 7: the death tolls per 100,000 inhabitants are two orders of magnitude smaller in Asian countries than in the western countries listed above. A maximum of 3–4 daily deaths/100,000 inhabitants has been reported in Belgium, which is the mostly-affected country. Maxima of 1–2 daily deaths/100,000 inhabitants were reported in several Western Europe countries, as Spain, France, Italy, UK and Sweden, and in the USA.

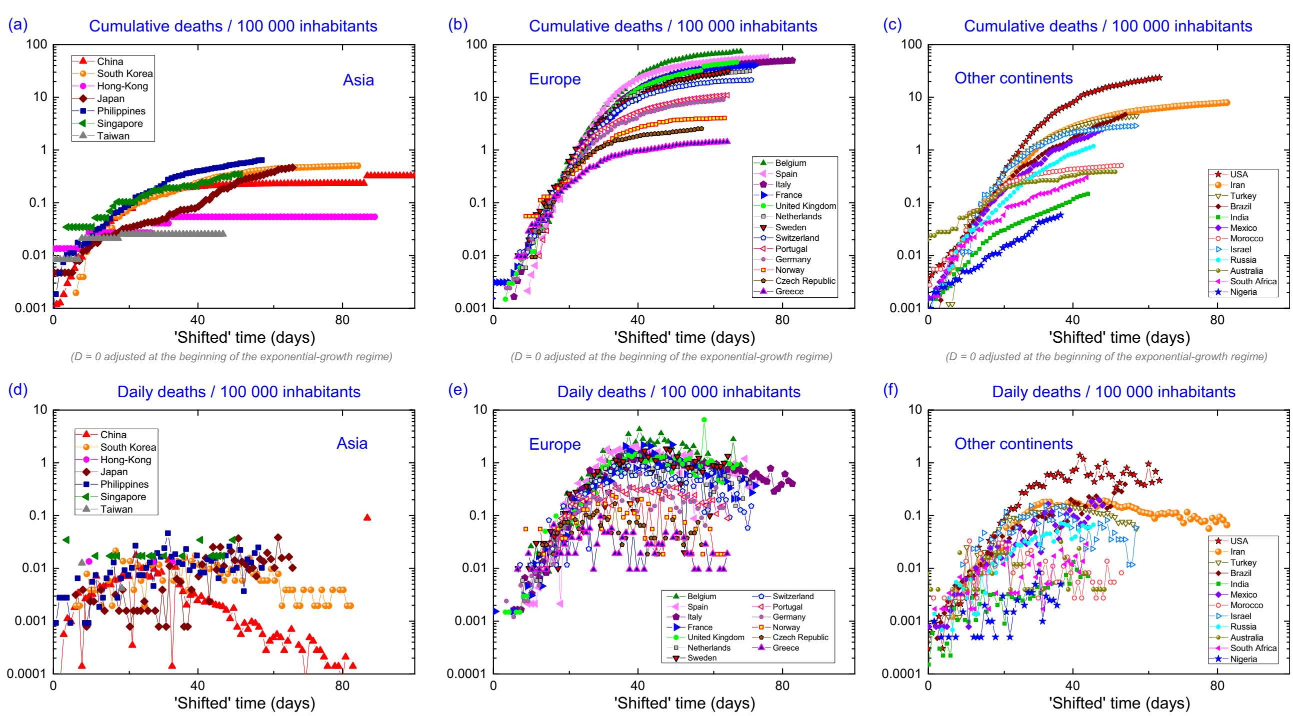

Figure 7. Cumulative and daily death tolls per 100,000 inhabitants for a selection of 32 countries worldwide. Cumulative deaths per 100,000 inhabitants versus "shifted" time (a) in Asian countries, (b) in European countries, and (c) in countries from other continents. Daily deaths per 100,000 inhabitants versus "shifted" time (d) in Asian countries, (e) in European countries, and (f) in countries from other continents.

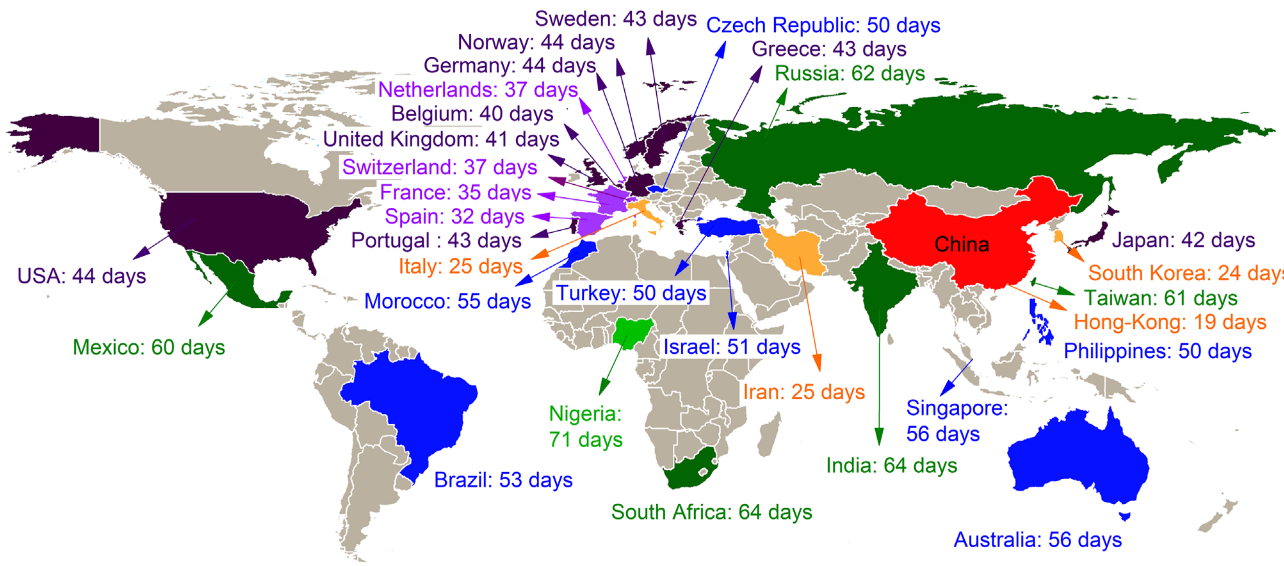

Figure 8. World map and shifts in days of the beginning of the epidemic exponential-growth regime 2, for a selection of 31 countries, in comparison with China.

The spread of the pandemic is heterogeneous in Europe, and countries as Greece, Czech Republic, and Norway succeeded to contain it to $<$ 0.2 daily deaths/100,000 inhabitants, which is 5–10 times higher than the rates $<$ 0.05 daily deaths/100,000 inhabitants reported in Asian countries.

In the Supplementary Materials (Section S4 "Focus on the propagation of COVID-19 in France"), we show that similar inhomogeneity can be observed at a national scale, once regions and departments are considered separately. In other parts of the world (Africa, South America, Australia), the reported death numbers indicate a situation in-between that in Asia and that in mostly-affected western countries, due to the combination of late arrivals of the virus on the territory and possible local specificities (density of population, weather, etc.).

The world map in Figure 8 indicates the delays in the worldwide propagation of the COVID-19. The "shifts" in time used in the data plotted in Figure 7, in relation with the delayed onset of the exponential-growth regime 2 (see Fig. 4) are indicated for the countries considered here. This Figure shows that, four months after the first cases reported in China, all parts of the globe have been hit by the pandemic. After Asia, the pandemic arrived in South-West Europe and then expanded to the North and East of Europe, to the USA, and finally to the rest of the world.

Table 1 summarizes the situation for the countries considered here. It shows that the pandemic spread in the different countries is weakly-correlated with the date of arrival of the pandemic. This means that the experience gained by early-hit countries did not benefit to all lately-hit countries. The countries considered here are classified in a four-group scheme, depending on the degree of spread of the pandemic in their population on 8 May 2020:

→ *Group A*: Taiwan, Hong Kong, Japan, China, Singapore, Philippines, South Korea, Nigeria, South Africa, India, India, Australia, Morocco.
  ◦ The pandemic was contained to low levels, with less than 0.5 cumulative death/100,000 inhabitants. In most of these countries measures were taken in reactive and efficient way. The early measures (including high-level of testing, massive use of masks, insulation of detected cases) taken in some of these countries, as South Korea [55] and Hong Kong [56], permitted to avoid lockdown and to preserve a "minimal" economic activity. In other countries from Group A, a late arrival of the virus combined with local specificities (weather, age of population, etc.) perhaps helped to keep low death tolls in the beginning of May 2020.

→ *Group B*: Russia, Mexico, Greece, Brazil, Czech Republic, Israel, Turkey, Norway.
  ◦ These countries have been "weakly" affected by the pandemic, with between 1 and 5 cumulative deaths/100,000 inhabitants. In Europe, the results obtained in Greece, Czech Republic, and Norway contrast with those from their neighbors, most of them being in Group D. In the beginning of May 2020, the daily death tolls in Brazil, Mexico, and Russia continued increasing, and these countries may later downshift to Group C.

→ *Group C*: Iran, Germany, Portugal.
  ◦ From the official tolls, these countries are in a better situation than the countries from Group D. However, the situation is not optimal, since between 8 and 11 cumulative deaths/100,000 inhabitants were reported, which is more than a factor 20 higher than in the countries from Group A.

→ *Group D*: USA, Switzerland, the Netherlands, Sweden, UK, France, Italy, Spain, Belgium.

- This "group" is composed of countries from Western Europe and North America. Fashionable theories (herd immunity scenario [4–6]) and a confidence in health system perhaps led to a delayed state reaction against the pandemic propagation. Lockdown measures were applied late, when the numbers of cumulative deaths were already high, leading to much higher epidemic peaks and cumulative death tolls than in the countries from the Groups A–C. Between 20 and 75 cumulative deaths/100,000 inhabitants were counted on 8 May 2020 in these countries. A maximum of 3–5 daily deaths/100,000 inhabitants was reported in Belgium, and maxima of 1–2 daily deaths/100,000 inhabitants were reported in Spain, France, Italy, Sweden, UK and USA. In the beginning of May 2020, Sweden was the last strongly-affected country having the strategy to reach herd immunity without lockdown measures [38]. Its situation may continue worsening until herd immunity is achieved or until the Swedish government changes its strategy.

Table 1 also indicates that a clear relation exists between the earliness of application of lockdown measures and the efficiency to contain the pandemic spread. From most of the countries considered here, the epidemic peak, i.e., the center of the maximal plateau in the daily deaths variation is observed 20–25 days after the application of lockdown. The effects of a lockdown are, thus, observable quite late, which indicates the importance of applying it immediately after the start of an epidemic wave. The Section S2 "Consequences of a delay in the lockdown start" in the Supplementary Materials presents this point in more details. Early lockdown dates, before or a few days after the $d = 0$ start of the exponential-growth regime 2, characterize the countries from Group A (those which needed to apply lockdown). On the contrary, all countries from Group D (with the exception of Sweden) applied a late lockdown, about three weeks after the start of the exponential-growth regime 2. Most countries from Groups B and C are in an intermediate situation.

Figure 9 presents the time variation of the ratio between the cumulative deaths and confirmed cases for the selection of countries considered here. The "shifted" times used in this graph were defined by considering normalized death tolls per 100,000 inhabitants (see Fig. 7). Even in the case of a perfect "measurement", where the cumulated deaths and confirmed cases would be well-estimated, their ratio would not be constant with time, due to the time delay between contaminations and deaths. For a perfect "measurement", this ratio would lead asymptotically to the fatality rate of the epidemic at the end of an epidemic wave. However, this rate is not universal, since it can vary from one country to another, due to different weather conditions, population characteristics (age, obesity, density, etc.), medical care means, and possibly virus mutations.

In real life, measurements are imperfect and the means to detect COVID-19 cases are more or less efficient, depending on the country. The large scattering of data in Figure 9 mainly results from these counting limitations. Since cumulative death tolls are expected to be more reliable than confirmed case tolls, the ratio at the end of an epidemic wave reaches a value higher than the fatality rate when measurements are imperfect. We can suspect that a small country doing a high number of tests may be able to reach a ratio close to the fatality rate. This may be the case of Hong-Kong, for which the ratio converges to 0.4% at the end of the epidemic wave and may be compatible with a fatality rate of $\approx$ 0.5%. This rate is in good agreement with estimates of fatality rates, ranging from 0.5 to 1.5%, proposed in references [9, 10, 57]. We note that a smaller ratio 0.1% was observed in Singapore in the beginning of May 2020, but an epidemic wave was still on-going and this ratio could converge to a higher value after the wave.

From this rough, but presumably reasonable assumption of a fatality rate of 0.5%, we can estimate the order of magnitude of the already-infected part of the population in each country by applying a factor 200 to the cumulative death number. Due to the delay between infections and their consequences (including deaths), this estimation is more appropriate for countries at the end of an epidemic wave. Table 1 shows the estimated proportions of the population infected by the coronavirus SARS-CoV-2 at the date of 29 April 2020: less than 0.1% in countries of the Group A, between 0.1 and 1% in countries of the Group B, between 1 and 2% in countries of the Group C, and more than 4% in countries of the Group D. A maximum of 15% of infected people is estimated for Belgium, which is the mostly-affected country. For all countries from Group D, these tolls remain far below from the proportion of 60% expected to achieve herd immunity. We note that lower proportions may be sufficient to reach herd immunity in areas with heterogeneous densities of population [58].

In the mostly-affected parts in Europe (as department Bas-Rhin in France, see Section S4 "Focus on the propagation of COVID-19 in France" in the Supplementary Materials), a maximum of about 100 cumulative deaths per 100,000 inhabitants was reported and we can estimate that 20% of the population was contaminated. In these highly-affected areas, the number of contaminated cases is still far from the proportion of 60%. On 8 May 2020, New-York City was one of the mostly-affected areas in the world, with 19,561 cumulative deaths reported [24], which corresponds to 0.235% of its population of 8.3 million inhabitants [59]. Assuming a fatality rate of 0.5%, we can estimate that 47% of the population was infected by the virus. New-York city may be soon one the first areas with several million inhabitants where herd immunity may be achieved. These rough estimations also confirm that herd immunity would be an option of very high human cost if achieved on a worldwide scale (see Section S3 "What could be expected without containment measure?" in the Supplementary Materials).

Table 1. Comparison of characteristic times in the propagation of the pandemic, deaths rates (maximum daily deaths and cumulative death tolls, normalized per 100,000 inhabitants, observed till the 8 May 2020) for the selection of 32 countries considered here. Lockdown start and lift dates are from references [26–36, 40–54]. Assuming a fatality rate of 0.5%, the percentage of population already hit by the virus is estimated for each country. The countries are ranked into four Groups A–D, depending on the degree of propagation of the pandemic in their population.

Country	Start of regime 2 ($d = 0$)	Delay in comparison with China	Lockdown start	Lockdown start (shifted time d)	Peak in daily reported cases/deaths (shifted time d)	Lock-down lift	Lockdown lift (shifted time d)	Daily deaths/100,000 inhabitants (maximum) 8 May 2020	Cumulative deaths/100,000 inhabitants 8 May 2020	Estimation of contaminated population (%) 8 May 2020	Group
Taiwan	22 Mar	61	–	–	1/–	–	–	< 0.01	0.03	0.005	A
Hong Kong	9 Feb	19	–	–	48/–	–	–	< 0.01	0.05	0.01	A
China	21 Jan	0	23 Jan	2	14/26	8 Apr	78	0.01–0.02	0.32	0.06	A
Singapore	17 Mar	56	7 Apr	21	34/–	–	–	0.01–0.02	0.34	0.07	A
Japan	03 Mar	42	–	–	44/–	–	–	0.01–0.03	0.46	0.09	A
South Korea	14 Feb	24	–	–	16/37	–	–	0.01–0.02	0.50	0.10	A
Philippines	11 Mar	50	15 Mar	4	–/–	–	–	0.01–0.03	0.64	0.13	A
Nigeria	1 Apr	71	30 Mar	−2	–/–	–	–	0.002–0.01	0.06	0.01	A
India	25 Mar	64	25 Mar	0	–/–	–	–	0.004–0.015	0.15	0.03	A
South Africa	25 Mar	64	26 Mar	2	–/–	–	–	0.01–0.03	0.30	0.06	A
Australia	17 Mar	56	23 Mar	6	10/–	–	–	0.01–0.03	0.38	0.08	A
Morocco	16 Mar	55	20 Mar	4	36/24	–	–	0.01–0.03	0.51	0.10	A
Russia	23 Mar	62	31 Mar	8	–/–	–	–	0.05–0.07	1.2	0.24	B
Greece	4 Mar	43	23 Mar	19	26/–	–	–	0.03–0.07	1.4	0.29	B
Mexico	21 Mar	60	21 Apr	31		–	–	0.15–0.2	2.5	0.50	B
Czech Republic	11 Mar	50	14 Mar	3	19/27	–	–	0.1–0.15	2.6	0.51	B
Israel	12 Mar	51	–	–	21/32	–	–	0.1–0.2	2.9	0.58	B
Norway	5 Mar	44	12 Mar	7	22/36	20 Apr	46	0.1–0.25	4.0	0.81	B
Turkey	11 Mar	50	–	–	33/38	–	–	0.15	4.4	0.88	B
Brazil	15 Mar	53	–	–	–/–	–	–	0.3–0.4	4.75	0.95	B
Iran	15 Feb	25	–	–	43/41	–	–	0.15–0.2	7.9	1.6	C
Germany	5 Mar	44	21–23 Mar	16–18	24/41	–	–	0.2–0.5	9.0	1.8	C
Portugal	4 Mar	43	19 Mar	15	28/36	–	–	0.3	10.9	2.2	C
Switzerland	27 Feb	37	17 Mar	19	28/40	–	–	0.5–1	21.2	4.2	D
USA	5 Mar	44	19 Mar–7 Apr	14–33	–/–	–	–	0.5–1.5	23.5	4.7	D
The Netherlands	27 Feb	37	23 Mar	25	40/44	–	–	0.7–1.5	31.3	6.3	D
Sweden	4 Mar	43	–	–	–/–	–	–	1–2	31.8	6.4	D
France	26 Feb	35	17 Mar	20	40/45	–	–	1–2	40.2	8.0	D
UK	02 Mar	41	23 Mar	21	–/–	–	–	1–1.5	46.3	9.3	D
Italy	15 Feb	25	8 Mar	22	37/41	–	–	1–1.5	49.8	10.0	D
Spain	22 Feb	32	15 Mar	22	35/39	–	–	2	56.3	11.3	D
Belgium	1 Mar	40	18 Mar	17	39/45	–	–	3–5	74.1	14.8	D

Discussion

The Asian countries from the Group A succeeded to contain the spread of the pandemic to low levels. In China, lockdown was applied early after the identification of a starting epidemic wave [30]. An epidemic peak with a rate of 100–200 deaths per day was reached 20 days later, and lockdown was lifted 80 days after its application [31], while an average rate of < 1 death per day was reported. In South Korea, an early reaction permitted to isolate most of the contagious cases and to early curb the pandemic dynamics, with a total of 250 cumulative deaths counted at the beginning of May 2020. To keep a low number of contagious cases, and thus, a low number of new contaminated cases,

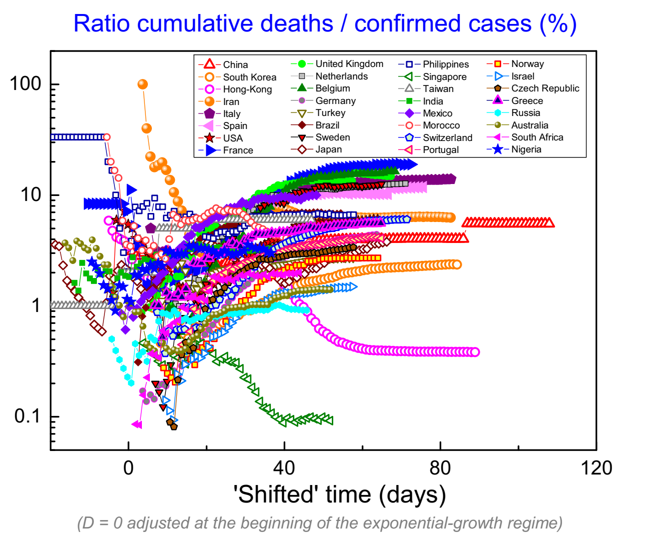

Figure 9. Ratio between cumulative deaths and confirmed case tolls for the selection of 32 countries considered here.

the strategy of Asian countries of Group A can be summarized by the main measures [55, 56]:

→ Systematic tests and survey of the population combined with a fast isolation of new contaminated cases.
→ A massive use of protection masks.
→ A strict surveillance of national frontiers, with quarantine imposed to all new incomers.

The results obtained so far can be considered as a validation of this strategy. They may allow continuing an economic activity without risking the resurgence of large epidemic waves. Bilateral agreements between "safe" countries may permit to reopen progressively the frontiers and to restart economic exchanges.

In most of the countries from Group B, after the end of the first epidemic wave, the levels of contagious people are or will remain low enough to hope avoiding a second devastating wave, once appropriate measures are taken. A similar method to that applied in Asian countries may constitute a healthy strategy for the forthcoming weeks/months. A difficulty will be to avoid infections exported by their neighbors from Groups C and D.

In the countries from Groups C and D, the successful strategy and the experience gained by early-hit countries in Asia was not considered, and confused political communication and late measures led to tens of thousands cumulative deaths in many of them. A patient approach, with a lockdown lift, when the number of daily death tolls would be of the order of a few units per country (see Fig. 6), may allow to safely reach a situation similar to that of China and South Korea after their first epidemic waves. On the contrary, a lockdown lift while the number of contagious people would remain high could be risky. This second option was chosen by several of these countries (see for instance [39]). A re-opening of the frontiers inside the Schengen area and a non-massive use of protection masks may constitute additional difficulties in the Western Europe countries from Group D.

Summary

The graphs and the phenomenological descriptions presented here emphasize the importance of applying reactive and efficient measures against the propagation of the COVID-19 pandemic, at least if one wants to fight against it. Such intensive effort may be needed as long as herd immunity is not achieved, either by a global vaccination campaign or by a free (voluntarily or not) spread of the pandemic in a population. The COVID-19 pandemic revealed the weak preparation of several countries, in particular in Western Europe and the USA. An application of the methods which proved to be successful in Asia, rather than alternative and risky methods, is suggested for the countries facing strong epidemic waves. Additional complications could come from a seasonality of the virus, which would prevent reaching herd immunity without a vaccine.

In beginning of May 2020 several questions are still open:

→ Are the measures taken in Asian countries, as China and South Korea, sufficient to limit COVID-19 resurgences to ripples associated with a "few" tens or hundreds of cumulative deaths? Is it possible to maintain the pandemic to such low level, during 10–20 months, i.e., the expected timescale for a vaccine available in large quantities?
→ How will Western Europe countries proceed to try avoiding resurging waves? Will they apply similar measures than the Asian countries, or will they experiment alternative methods? In particular, can a hasty lift of lockdown lead to the resurgence of epidemic waves of significant magnitude? In such case, could herd immunity be achieved rapidly?
→ How the situation will evolve in the countries of South America, Africa and Oceania, where the late arrival of the pandemic, possibly combined to local specificities (weather, age of population, etc.), permitted them not to be heavily-hit in the beginning of May 2020?

Nomenclature of abbreviations

N	Number of cumulative deaths.
$D = 0$	Corresponds to the date at which $N = 1$ cumulative death is extrapolated from the exponential growth regime.
n	Number of cumulative deaths normalized per 100,000 inhabitants.
$d = 0$	Corresponds to the date at which $n = 0.001$ cumulative deaths/100,000 inhabitants is extrapolated from the exponential growth regime.
F	The ratio of cumulative deaths at the beginning of the lockdown and at the end of the epidemic wave.

Supplementary materials

The supplementary materials of this article is available at https://www.4open-sciences.org/10.1051/fopen/2020005/olm

Supplementary data: Australia.dat, Brazil.dat, Belgium.dat, China.dat, China_smoothed.dat, Czech_Republic.dat, France.dat, Germany.dat, Greece.dat, Hong_Kong.dat, India.dat, Iran.dat, Israel.dat, Italy.dat, Japan.dat, Mexico.dat, Morocco.dat, Netherlands.dat, Nigeria.dat, Norway.dat, Philippines.dat, Portugal.dat, Russia.dat, Singapore.dat, South_Africa.dat, South_Korea.dat, Spain.dat, Sweden.dat, Switzerland.dat, Taiwan.dat, Turkey.dat, UK.dat, USA.dat

Figure S1: Comparison of the propagation of the pandemic in a selection of 32 countries.

Figure S2: Evolution of cumulative and daily death tolls per 100,000 inhabitants in China, South Korea, Italy, Spain, France (mainland) and the USA.

Figure S3: (a) Fit by an exponential law of the cumulative deaths variation in regime 2. This universal law is followed by all countries in this regime. (b) Extrapolation of the final cumulative death number expected in France, as a function of the starting date of lockdown. A similar epidemic decline as that reported in China, and a factor $F = 160$ compatible with 28,000 cumulative deaths, for a lockdown starting on 17 March, are assumed.

Figure S4: Fit by an exponential law of the variation with time of cumulative death tolls in Italy and France, and its extrapolation after the start of lockdown.

Figure S5: Focus on cumulative and daily deaths in French metropolitan regions.

Figure S6: Map of France and shift in days of the beginning of the epidemic exponential-growth regime 2 for the metropolitan regions in comparison with China.

Figure S7: Cumulative deaths, daily deaths, and normalized daily deaths per 100,000 inhabitants as function of date or "shifted" time for a selection of French departments in region Ile-de-France and in the East of the country.

Figure S8: Map of East of France and shift in days at the beginning of the epidemic exponential-growth regime 2 for a selection of departments, in comparison with China.

Figure S9: Variation of (a) cumulative and (b) daily death tolls in France, in regard with political measures and the last mass events.

S5 – Supplementary References

Conflict of interest

Author declared no conflict of interests.

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