A simple mathematical model for a real-time tracking of the new coronavirus (COVID-19) outbreak.

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Abstract

A simple 0-D model has been developped to follow in real-time the COVID-19 outbreak in France, but also in seven others countries. While China and South-Korea are reaching progressively a full control of the outbreak, France, despite what is said officially, is not on the path to control it (at the time of the 22th of March). Indeed, the residual contamination rate, that is the key parameter of the model, is about 14 times higher than the Chinese or the Korean ones. In these conditions, if the outbreak is not fully controlled in the coming weeks, and supposing that the coronavirus remains highly contagious as it is today, about 60 % the french population will be contaminated very soon (in less than two months approximately), which could lead to a dramatic increase of number of deaths, but also of the number of very sick people requiring continuous respiratory support, far above hospitals capacities, by several orders of magnitude. The Italian outbreak whose time evolution is also very well described by the model, is already facing a major health issue. France is just a week behind according to the analysis of the time evolution of the data. Besides elementary precautions, a strict quarantine which has been succesfully applied in China and in a different manner in South-Korea, but also on the cruise liner Diamond Princess, is the only path to reduce drastically the exponential growth rate of the outbreak, limiting the number of deaths (on the basis of the parameters that give actually the best fit of the observed time evolution, and if nothing has changed in between), and also the dramatic overload of the hospitals, especially in the continuous health care units. The numerical tool here developped allows to follow easily, on a daily basis, the evolution of the outbreak, and the effectiveness of the actions that have been decided. Various scenarii have been also studied, in particular if the number of officialy certified contaminated people is slightly or strongly under-estimated. For countries controlling the outbreak by quarantine (like China and South-Korea), the risk that it restarts is extremely high (most of the population is not immune to the virus, even if the outbreak is stopped by quarantine), and therefore, a two weeks quarantine at the borders of these countries must be set-up to avoid a possible of the outbreak (as done). Consequently, travels between countries will become very complicated either for professional or personal purposes. This situation may last a very long time, as long as the virus is active or a massive vaccination of the world population has not been carried out. The consequences for the world economy may be disastrous.

1 Introduction

The outbreak of the new coronavirus (COVID-19) that emerged in China in December 2019 is the object of strong interest by everybody, and seems to be a very dangerous health problem at the world scale. Journalistic coverage is intense and very anxiety-provoking. The coronavirus outbreak raises many questions (fatality rate, hospital overload,...) that is difficult to answer without a quantitative tool to evaluate the effectiveness of the confinement procedures in particular to control the disease.

For this purpose, a very simple zero-dimensional model of the outbreak has been developped, which can be easily compared to daily observations. From this model, the challenges are clearly highligthed, as well as the chances to block successfully the outbreak prior to the development of a vaccine. The model here presented has been applied successfully to several representative countries where the coronavirus outbreak is well developped: Canada (Quebec), China, France, Germany, Iran, Italy, South-Korea, Spain, Sweden, Switzerland, United-Kingdom and United-State of America. The comparison clearly highlights the effect of a strong quarantine on the

long term evolution of the outbreak, long being here about 120 days or 4 months. It is also possible to compare the various fatality rate, and try to understand larges differences between countries concerning the outbreak evolution. Concerning this point, a better undertstanding of the actual outbreak status can be extracted from the analysis of the outbreak in the Diamond Princess boat, where 4000 people where blocked by Japanese authorities during less than a month. Detailed are given in this Sec. 4.2.2 and this led to develop a low fatality rate scenario, applied to France first before to be generalized to other countries after validation.

The approach here presented is valid from the beginning to the end of the outbreak, taking into account of the finite size of the reservoir of people that can be contaminated. It gives therefore an indication if the outbreak will stop (naturally or artificialy thanks to the quarantine) and when, and the total number of people who will die because of the virus. It indicates also time at which the health system will become strongly overloaded. The reservoir effect is accounted by considering the probability of contamination in addition to the rate of contamination.

This note will be regularly updated on the basis on data obtained principally from World Health Organization, Wikipedia®, CDC at Hoston in US. The latter site gives very interesting details to prevent or limit contamination. Another interesting website can be visited here for the outbreak, in particular in Iran. A very well documented worldwide database on the coronavirus outbreak is also available here.

Finally, the code given in Appendix may be used freely (Matlab software required).

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Note: Date/time in square brackets in the titles of the figures correspond to the date/time at which calculations have been performed.

Contents

2 The model

2.1 The elementary processes

The contamination process is individual by inter-human contacts. Here the details of the contamination are not considered,. The rate of contamination per people and per day is the main parameter to quantify the growth rate of the contaminated people. It may be adjusted to fit observations, and depending its evolution, it is possible to foresee how the outbreak will evolve, i.e. if it can be controlled or not, manageable or not.

Let suppose that one person is sick but don't know its own health status. During the incubation period τ_i, N_i persons will catch the virus by close contact and develop later the disease. The individual mean rate of contamination per person and per day is then

$$q_c(t) = N_i(t)/\tau_i \tag{1}$$

knowing the mean incubation time is constant and about $\tau_i = 6.4$ days from studies of the COVID-19 at Wuhan [7], a number which is subject of very large fluctuations. More references may be found here.

One must introduce also the probability of contamination at time t, $p_c(t)$, related to the chance that sick people can effectively encounter non-sick people. This parameter plays a minor at the beginning of the outbreak and is cloe to one. However, it is important to introduce it in order to simulate the natural end of the outbreak, when all people have been contaminated. Details will be discussed later. When $p_c(t)$ tends towards zero, this mean that herd immunity is close to be achieved.

The daily increase of sick people is then given by the simple law

$$\triangle N_s(t) = p_c(t-1)\, q_c(t-1)\,(N_s(t-1) - N_h(t-1) - N_d(t-1))\,\Delta t \tag{2}$$

and the cumulative number of sick people at time t is

$$N_s(t) = \triangle N_s(t) + N_s(t-1) \tag{3}$$

or

$$N_s(t) = (\Delta t q_c(t-1)\, p_c(t-1) + 1)\, N_s(t-1) - (\Delta t q_c(t-1)\, p_c(t-1))\,(N_h(t-1) + N_d(t-1)) \tag{4}$$

where $N_h(t)$ is the cumulative number of healed people, and $N_d(t)$ is the cumulative number of deaths. Here, $\Delta t = 1$ days. For the COVID-19, $N_d \ll N_h$ and N_d may be neglected.

The product $p_c(t)\, q_c(t) \equiv R_c(t)/\tau_i$ is nothing but the reproductive control number, in presence of control measures as defined by Kermack & McKendrick. So, according to the above definitions

$$R_c(t) = p_c(t)\, N_i(t) \tag{5}$$

and at the beginning of the outbreak, i.e. $R_c(t=0) = R_0$ is the well known basic reproduction number. Since at that time, $p_c(t=0) = 1$,

$$R_0 = N_i(t=0) = q_c(t=0)\,\tau_i \tag{6}$$

and if $R_c < 1$ or $N_i < 1$, the outbreak stops. This corresponds in the model to $q_c < 1/\tau_i$, or $q_c < 0.25$ approximately with $\tau_i = 4$ days. So, the longest is the incubation time, the more difficult is the control of the outbreak. This is the reason why the COVID-19 is so difficult to be controlled without a strong confinement of the population. Discussion of R_0 is given in Sec. 4.2.1.

In the calculations, it is assumed that the reservoir of people that can be contaminated is initially almost infinite. Therefore, when the outbreak is starting, $p_c(t) = 1$. If reservoir effects become significant, like for the passengers in the contaminated cruise liner Diamond-Princess after several days, then the exact balance between people that can be contaminated N_c, sick people N_s and N_h healed people that cannot be recontaminated (recontamination seems negligible as far as the virus genetic variability is small) must be properly taken into account,

$$N_c + N_s = N_{tot} \tag{7}$$

with N_{tot} constant[1]. This is the classical compartmental approach of the outbreak, in which different populations are considered, which led to the SIR or SEIR models. The reservoir effect can be accounted by the simple relation

$$p_c(t) = \frac{N_c(t)}{N_{tot}} = 1 - \frac{N_s(t)}{N_{tot}} \tag{8}$$

and without any control measures, the outbreak stops if

$$p_c(t) R_0 < 1 \tag{9}$$

or

$$(1 - f) R_0 < 1 \tag{10}$$

where $f = N_s(t)/N_{tot}$ is the fraction of the population that is naturally immunited (infected or protected by a vaccine). Therefore,

$$f = 1 - \frac{1}{R_0} \tag{11}$$

Consequently, the larger is R_0, the larger the fraction of the immunited population should be to stop naturally the propagation of the virus. So the upper limit of the people that can be contaminated is

$$N_{\max} = \left(1 - \frac{1}{R_0}\right) N_{tot} \tag{12}$$

or

$$N_{\max} = \left(1 - \frac{1}{q_{c0}\tau_i}\right) N_{tot} \tag{13}$$

For disease with large R_0, a very large fraction of the population should be immunited, almost 95 % for the measles. So, in order in incorporate this limitation, a modified version of $p_c(t)$ is considered in the calculations

$$p_c(t) = 1 - \frac{N_s(t)}{N_{\max}} \tag{14}$$

Finally, if the outbreak is supposed to be suppressed by confinement, the reservoir of non-immunited people remains very large, and $p_c(t) \simeq 1$.

The number of healed people is simply described by a delay effect (time to recover)

$$N_h(t) = (1 - \delta_d) N_s(t - \tau_h) \tag{15}$$

where τ_h is healing time, and δ_d the fatality rate. While $N_s(t)$ may saturate, $N_h(t)$ can still increase, because of the delay, since $N_h(t) \leq N_s(t)$. Usually, as for the flue, $\tau_h = 7$ days, but here to reproduce the time evolution of the outbreak in China, $\tau_h = 14$ days gives better results. This number seems closer to some observations. This means that sick people recover in 14 days, once symptoms started. This has no impact on the initial rise of the outbreak. This explain why confinement time τ_c is about two weeks at minimum, since

$$\tau_c \simeq \tau_i + \tau_h \tag{16}$$

Finally, the outbreak is ending when the condition

$$N_s(t) - N_h(t) - N_d(t) < 1 \tag{17}$$

is fullfiled, i.e. when less than a single person is contaminated.

At $t = 0$, $p_c(t = 0) = 1$, since nobody is contaminated. At the end of the contamination, since everybody has been almost contaminated and are supposed to be immunited against the virus, $p_c(t) \simeq 0$, which means that the rate of contamination is always naturally decreasing, whatever the type of outbreak. Since the model here developped has no spatial dimension, only mean values matter, and one can consider the density of population only. It is therefore assumed that the virus spread quickly almost uniformly over the whole country, which is a

[1] It is assumed that the number of people that died from the virus is always small as compared to the initial value N_{tot}, which is valid as far as the fatality rate is small. So N_{tot} is a constant.

reasonable assumption, since spatially, the diffusion of the virus follows the Levy flight law : local and slow diffusion by close contacts described by $q_c(t)$ combined with very fast long distance diffusion of the disease by human transportation. It is interesting to observe that the spread of the outbreak of the coronavirus is identical at the scale of a country (cars, trains,...) or at the scale of the world (airplane). This the reason why stopping all types of long distance transportation sytems is the best way to localize the outbreak and hope to have a better control by local quarantine.

If $q_c(t) = q_{c0}$ is a constant and taking $p_c = 1$, which is the case at the starting point of an outbreak, prior to first measurements, Eq. 4 corresponds to a geometric series, that can be easily understood from the elementary process of contamination. Indeed,

$$\begin{aligned} N_s(t=1) &= (q_{c0}\Delta t + 1) N_s(t=0) = (q_{c0}\Delta t + 1) \\ N_s(t=2) &= (q_{c0}\Delta t + 1) N_s(t=1) = (q_{c0}\Delta t + 1)^2 \\ &\dots \\ N_s(t=n) &= (q_{c0}\Delta t + 1) N_s(t=n-1) = (q_{c0}\Delta t + 1)^n \end{aligned} \tag{18}$$

after n days.

Before entering into the analysis of the results, several values must be given. From Chinese data that can be obtained from the website Johns Hopkins university (USA), the rate of seriously sick people requiring hospitalization is about $\delta_{vs} = 15\,\%$, and those requiring in addition an active ventilation is estimated to $\delta_{vsv} = 6\,\%$ from recent french data, while the mortality rate is about $\delta_d = 1.5\,\%$, a bit lower than in China. These numbers are just a rough estimate, and may be adjusted for the outbreak in France, in particular for the mortality rate, since advanced medical treatments may be used. It should be recalled that the number of respirators in continuing care units is 1165 in France in January 2020 (offical government number).

From Eq. 4, it is possible to calculate the number of very sick people $N_{vs}(t)$ requiring hospitalisation, very sick people requiring intensive care with active ventilation $N_{vsv}(t)$and dead people $N_d(t)$. Based on the same approach as for $N_s(t)$, the cumulative number $N_{vsv}(t)$ is

$$N_{vsv}(t) = \delta_{vsv} N_s(t) \tag{19}$$

where δ_{vsv} is the fraction of sick people that needs ventilation and the daily number of people in the intensive care unit is then

$$n_{vsv}(t) = N_{vsv}(t) - N_{rvsv}(t) \tag{20}$$

where $N_{rvsv}(t)$ is the cumulative number of people that have left the intensive care unit after a time τ_{vsv}, or $N_{rvsv}(t) = N_{vsv}(t - \tau_{vsv})$

Same calculations can be performed with standard care unit, $N_{vs}(t)$, while for deaths

$$N_d(t) = \delta_d N_s(t - \tau_d) \tag{21}$$

considering that δ_{vs}, δ_{vsv} and δ_d are the relativative fractions. By definition $N_h(t) \simeq (1 - \delta_d) N_d(t)$ if both . At present time, no specific delay τ_{vs}, $\tau_{vsv}$and τ_d is introduced for each sub-population, but this may be considered, since very sick people requiring intensive care recover or die after 20 days approximately, three times longer than the standard recovery time τ_h. Since their fraction is very small in the early phase of the outbreak dynamics, the feedback may only be expected if the herd immunity reach its maximum, are if the confinement is successfull to reduce daily variation of N_s. So, $\tau_{vs} = \tau_{vsv} = \tau_d = 0$ for the early phase of the outbreak. For China, which has almost reached the end of the outbreak, it is clearly visible that the simulated $N_d(t)$, which has by definition the same time dynamics like N_s in the model, is peaked earlier than observed, and then decreases more slowly after the outbreak peak (see Fig. 38). In the intense phase of the outbreak, it was reported that Chinese authorities have hidden the actual daily number of deaths, to reduce the political impact of the outbreak. This option is possible since the daily number of deaths in South-Korea seems to peak at the same time like N_s, though the low number of deaths makes it difficult to appreciate, regarding the uncertainty (see Fig. 48). More details will have to be analyse on this point. Finally, changing τ_d may have an impact on the value of δ_d. This may be one of the difficulty to identify accurately the fatality rate. So

far, with $\tau_d = 0$, the standard δ_d values obtained from of more advanced modeling tools allows to reproduce well the observations.

Due to possible onset of efficient medications during the outbreak, δ_{vs}, δ_{vsv} and δ_d may themselves be time dependent. Such a possibility is not yet considered but may be easily introduced in the calculations. Regarding the uncertainty from daily variations of $N_s(t)$, this may be considered at the end of the outbreak only. None of the outbreak simulations are able to be accurate thanks to this problem, at the early stage.

2.1.1 The social distancing model

Finally, the quarantine policy, i.e. the social interaction is modeled by a simple smooth step or sigmoid function of the form

$$q_c(t) = (q_{c0} - q_{c\infty}) \left(\frac{1 + \exp(-\tau_{ref}/\triangle\tau)}{1 + \exp((t - \tau_{ref})/\triangle\tau)} \right) + q_{c\infty} \tag{22}$$

in order to mimic the usual observed decrease of $q_c(t)$. Significance of parameters are simple: q_{c0} and $q_{c\infty}$ are respectively the initial and final rates of contamination, τ_{ref} is the mean time at which the slope is maximum between the two levels of the contamination rates, and $\triangle\tau$ describes the time evolution at which $q_c(t)$ evolves from q_{c0} to $q_{c\infty}$. It is important to recall that $R_0 = q_{c0}\tau_i$, and $R_c = q_c\tau_i$.

At $t = 0$, $q_c(t) = q_{c0}$, while $\lim_{t\to\infty} q_c(t) = q_{c\infty}$. If the quarantine is realeased at a time t_{rel}, and the outbreak restarts, the above model may still be applied, but with values corresponding to the new situation. The corresponding formula is then

$$q_c(t) = (q_{c0}(t) - q_{c\infty}(t)) \left(\frac{1 + \exp(-(\tau_{ref}(t) - t_{rel})/\triangle\tau(t))}{1 + \exp((t - \tau_{ref}(t))/\triangle\tau(t))} \right) + q_{c\infty}(t) \tag{23}$$

for $t > t_{rel}$. It is interesting to observed that once the outbreak starts, $q_{c0} \simeq 0.75 - 1$ in almost all countries. If the population has not realized that an outbreak is developing, it stays at the initial value during a long period. Then the population starts to self-protect, and $q_{c\infty} \simeq 0.2 - 0.3$. The time τ_{ref} is a good indicator at which this occurs, and $\triangle\tau$ the speed at which the information propagates in the population. Roughly, $\triangle\tau \simeq 2$ (See Table 1). After, this natural $q_{c\infty}$ stays almost constant, and from its value, one can derive if there is a chance that the outbreak will slow-down or not, i.e. if it will end naturally by herd immunity or by actively stopping the individual contamination, i.e. reducing social interactions. This is the purpose of this model.

In the case of change of $q_c(t)$ at a given time $t = t_{rel}$, the continuity of $q_c(t)$ leads to the relation

$$q_{c02} = (q_{c01} - q_{c\infty 1}) \left(\frac{1 + \exp(-\tau_{ref1}/\triangle\tau_1)}{1 + \exp((t_{rel} - \tau_{ref1})/\triangle\tau_1)} \right) + q_{c\infty 1} \tag{24}$$

so it is easy to determine any time $t = t_{rel}$ a change in the outbreak evolution.

2.2 Model analysis

2.2.1 Initial phase of the outbreak

When $\triangle t \to 0$, Eq. 2takes the differential form

$$dN_s = p_c q_c (N_s - N_h - N_d)\, dt \tag{25}$$

Let's consider first the simple case where $N_d \ll N_h \ll N_s$, and $p_c = 1$,which is the case in the early phase of outbreak or with a strong confinement, such that $N_s + N_h + N_d \ll N_{tot}$. In this case;

$$dN_s \simeq q_c N_s dt \tag{26}$$

or

$$\frac{dN_s}{N_s} \simeq q_c dt \tag{27}$$

Introducing the smooth step function Eq. 22,

$$\frac{dN_s}{N_s} = \left[(q_{c0} - q_{c\infty}) \left(\frac{1 + \exp\left(-\tau_{ref}/\triangle\tau\right)}{1 + \exp\left(\left(t - \tau_{ref}\right)/\triangle\tau\right)} \right) + q_{c\infty} \right] dt \tag{28}$$

or

$$\frac{dN_s}{N_s} = (q_{c0} - q_{c\infty}) \left(\frac{1 + \exp\left(-\tau_{ref}/\triangle\tau\right)}{1 + \exp\left(\left(t - \tau_{ref}\right)/\triangle\tau\right)} \right) dt + q_{c\infty} dt \tag{29}$$

and integrating both sides

$$\int_1^{N_s(t)} \frac{dN_s}{N_s} = (q_{c0} - q_{c\infty}) \int_0^t \left(\frac{1 + \exp\left(-\tau_{ref}/\triangle\tau\right)}{1 + \exp\left(\left(t - \tau_{ref}\right)/\triangle\tau\right)} \right) dt + \int_0^t q_{c\infty} dt \tag{30}$$

gives

$$\ln N_s = (q_{c0} - q_{c\infty}) \left(1 + \exp\left(-\tau_{ref}/\triangle\tau\right)\right) \int_0^t \frac{dt}{1 + \exp\left(\left(t - \tau_{ref}\right)/\triangle\tau\right)} + q_{c\infty} t \tag{31}$$

since $N_s\left(t = 0\right)) = 1$.

The indefinite integral being

$$\int \frac{dt}{1 + \exp\left(\left(t - \tau_{ref}\right)/\triangle\tau\right)} = t - \triangle\tau \ln\left(1 + \exp\left(\frac{t - \tau_{ref}}{\triangle\tau}\right)\right) \tag{32}$$

the integrated number of contaminated people is then

$$\ln N_s = (q_{c0} - q_{c\infty}) \left(1 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) \left[t - \triangle\tau \ln\left(1 + \exp\left(\frac{t - \tau_{ref}}{\triangle\tau}\right)\right) + \triangle\tau \ln\left(1 + \exp\left(\frac{-\tau_{ref}}{\triangle\tau}\right)\right) \right] + q_{c\infty} \tag{33}$$

so at $t = 0$

$$\ln N_s\left(t = 0\right)) = (q_{c0} - q_{c\infty}) \left(1 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) \left[-\triangle\tau \ln\left(1 + \exp\left(\frac{-\tau_{ref}}{\triangle\tau}\right)\right) + \triangle\tau \ln\left(1 + \exp\left(\frac{-\tau_{ref}}{\triangle\tau}\right)\right) \right] \tag{34}$$

and $N_s\left(t = 0\right)) = 1$ is well recovered.

Therefore

$$N_s\left(t\right) = \exp\left[(q_{c0} - q_{c\infty}) \left(1 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) \left[t - \triangle\tau \ln\left(1 + \exp\left(\frac{t - \tau_{ref}}{\triangle\tau}\right)\right) + \triangle\tau \ln\left(1 + \exp\left(\frac{-\tau_{ref}}{\triangle\tau}\right)\right) \right] \right] \tag{35}$$

or

$$N_s\left(t\right) = \exp\left[(q_{c0} - q_{c\infty}) \left(1 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) \left[t - \triangle\tau \ln\left(1 + \exp\left(\frac{t - \tau_{ref}}{\triangle\tau}\right)\right) + \triangle\tau \ln\left(1 + \exp\left(\frac{-\tau_{ref}}{\triangle\tau}\right)\right) \right] \right] \tag{36}$$

which means without people recovering, $N_s\left(t\right)$ is indefinitely growing if $q_{c\infty} > 0$.

If $t \ll \tau_{ref}$,

$$N_s\left(t\right) \simeq \exp\left[(q_{c0} - q_{c\infty}) \left(1 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) \left[t - \triangle\tau \ln\left(1 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) + \triangle\tau \ln\left(1 + \exp\left(\frac{-\tau_{ref}}{\triangle\tau}\right)\right) \right] \right] + \tag{37}$$

or

$$N_s\left(t\right) \simeq \exp\left[(q_{c0} - q_{c\infty}) \left(1 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) t + q_{c\infty} t \right] \tag{38}$$

or

$$N_s\left(t\right) \simeq \exp\left[\left(q_{c0} + (q_{c0} - q_{c\infty}) \left(1 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) \right) t \right] \tag{39}$$

and if $q_{c\infty} \ll q_{c0}$,

$$N_s\left(t\right) \simeq \exp\left[q_{c0} \left(2 + \exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right) t \right]$$

Conversely, if $t \gg \tau_{ref}$, Eq. 36 simplifies to

$$N_s(t) \simeq \exp\left[(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)\left[\tau_{ref}+\triangle\tau\ln\left(1+\exp\left(\frac{-\tau_{ref}}{\triangle\tau}\right)\right)\right]+q_{c\infty}t\right] \tag{40}$$

and even if $q_{c0} \gg q_{c\infty}$, at a given time t,

$$N_s(t) \simeq \exp(q_{c\infty}t) \tag{41}$$

So the importance of the residual contamination rate $q_{c\infty}$ on the long term evolution. As expected for $q_{c\infty}=0$, $N_s(t)$ becomes constant.

2.2.2 Peak of the outbreak enforced by confinement or social distancing

The peak of the outbreak is the key time at which the daily number of contaminated people starts to decrease. It can be the consequence of an herd immunity but also enforced by a strict confinement of people to reduce interactions, namely q_c. This case is not considered here.

Since the delay of recovery τ_h is long enough for $N_d \ll N_h \ll N_s$, the time at which the peak can be estimated with the approximation $N_h = N_d \simeq 0$. After the peak, the dynamics of the outbreak fully must consider N_h and N_d in the calculations and the equation to be solved is

$$dN_s = q_c(N_s - N_h - N_d)\,dt \tag{42}$$

Thanks to the above approximation that is specific to the coronavirus outbreak, τ_{peak} is determined by the equation $N_s''(t=\tau_{peak})=0$. From Eq. 36,

$$N_s'(t) = N_s(t)\left[(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)\left[1-\frac{\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}{1+\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}\right]+q_{c\infty}\right] \tag{43}$$

$$\begin{aligned}
N_s''(t) &= N_s'(t)\left[(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)\left[1-\frac{\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}{1+\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}\right]+q_{c\infty}\right] \\
&+ N_s(t)\left[(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)\left[\frac{1}{\triangle\tau}\frac{\exp^2\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}{\left(1+\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)\right)^2}-\frac{1}{\triangle\tau}\frac{\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}{1+\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}\right]\right] \\
&= N_s(t)\left[(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)\left[1-\frac{\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}{1+\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}\right]+q_{c\infty}\right]^2 \\
&+ N_s(t)\left[(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)\left[-\frac{1}{\triangle\tau}\frac{\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}{\left(1+\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)\right)^2}\right]\right]
\end{aligned} \tag{44}$$

such that τ_{peak} is solution of the equation

$$\left[(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)\left[1-\frac{\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}{1+\exp\left(\frac{t-\tau_{ref}}{\triangle\tau}\right)}\right]+q_{c\infty}\right]^2 = (q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)\frac{1}{\triangle\tau}\frac{\exp\left(\right.}{\left(1+\exp\right.}$$

and since $\tau_{peak} \gg \tau_{ref}$,

$$\frac{q_{c\infty}^2\triangle\tau}{(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)} = \frac{1}{\exp\left(\frac{\tau_{peak}-\tau_{ref}}{\triangle\tau}\right)} \tag{46}$$

or

$$\tau_{peak} \simeq \triangle\tau\ln\left[\frac{(q_{c0}-q_{c\infty})\left(1+\exp\left(-\frac{\tau_{ref}}{\triangle\tau}\right)\right)}{q_{c\infty}^2\triangle\tau}\right]+\tau_{ref} \tag{47}$$

If $q_{c\infty} < q_{c0}$, there exists always a peak of the outbreak. Time to reach the peak from the onset of the quarantine is therefore

$$\tau_{peak} - \tau_{ref} \simeq \triangle\tau \ln\left[\frac{1}{\triangle\tau}\frac{q_{c0}}{q_{c\infty}^2}\right] \tag{48}$$

in the limit $\tau_{ref} \gg \triangle\tau$ and $q_{c\infty} \ll q_{c0}$. Since for most countries, $q_{c0} \simeq 1$ and $q_{c\infty} \simeq 0.01$ to control the outbreak rapidly is to lower $\triangle\tau$. So, to set-up a strong quarantine on the shortest possible time scale. For $\triangle\tau = 1$, $\tau_{peak} - \tau_{ref} \simeq \ln\left[10^{+4}\right] \simeq 9$ days. In general, $\tau_{peak} - \tau_{ref}$is about two weeks. It worth to note that τ_{peak} is very sensitive to simulation parameters, and the if assumptions are not satisfied, the exact solution must be used instead of the approximate one.

At time corresponding to the outbreak peak, the outbreak speed is the faster, i.e. $dN_s/dt = q_c\left(N_s - N_h\right)$ is maximum. As far as $N_s'''\left(t\right) > 0$, it means that the outbreak is increasing, while the point at which $N_s'''\left(t\right) = 0$ indicates that it starts to slow-down.

2.2.3 Threshold to stop the outbreak

The contamination rate $q_{c\infty}$ is the key parameter to decide if it is possible to control the outbreak, namely stop it, regarding the initial value q_{c0} which gives the force of the outbreak. Such an approach require to solve Eq. 45, and depending the ratio $q_{c\infty}/q_{c0}$, to find if a solution τ_{peak}. Regarding the sensitivity of the Eq. 45, only a numerical determination can be carried out, as it has been done for France in Sec. 3.1.3

2.3 Residual evolution

Far from the outbreak peak, as reached by China and South-Korea, the daily number of cases or deaths is not going to zero as expected, but remains at a residual level, about 100 cases per day for both countries (30th of March). Such a persistence observed during more than 10 days indicates the high risk that the outbreak can restart. If $\triangle N_s$ is constant and independent of time, in the limit where $p_c \simeq 1$ and $q_c = q_{c\infty}$ it means that

$$\triangle N_s = q_{c\infty} \tag{49}$$

or in a differential formulation

$$dN_s = q_{c\infty} dt \tag{50}$$

which gives

$$N_s\left(t\right) = q_{c\infty}\left(t - t_p\right) + N_s\left(t = t_p\right) \tag{51}$$

so $N_s$should increase linearly with time, and since $N_h\left(t\right) = N_s\left(t - \tau_h\right)$,

$$N_h\left(t\right) = q_{c\infty}\left(t - t_p - \tau_h\right) + N_s\left(t = t_p\right) \tag{52}$$

so

$$N_s\left(t\right) - N_h\left(t\right) = q_{c\infty}\tau_h \tag{53}$$

If $q_{c\infty} < 1/\tau_h$, $N_s\left(t\right) - N_h\left(t\right) < 1$, so $N_s\left(t\right) - N_h\left(t\right)$ are almost identical, as expected, and the differene is constant. All quantities are linearly growing, $N_s\left(t\right)$, $N_h\left(t\right)$, but also the cumulative number of deaths.

3 The results

The application of the epidemic model has been applied to the seven main countries concerned by the coronavirus outbreak, i.e. China, France, Iran, Italy, South-Korea, Switzerland, and United-State of America. More recently, two other countries have been added: Germany and United-Kingdom, and the Quebec province of Canada.

China was the first country concerned by the outbreak which started at Wuhan, in December 2019. During a quite long period, the disease was underground, and exceptionaly strong

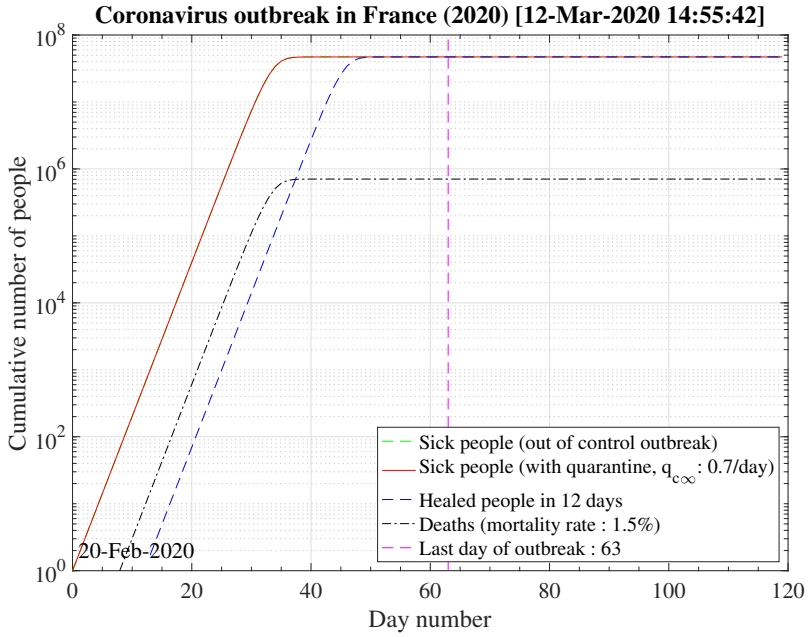

Figure 1: Number of contaminated and dead people by the coronavirus outbreak in France. The cases with and without quarantine are identical here, and follow Eq. **??** as far as $N_s \ll N_{tot}$.

quarantine was applied by end of January 2020. In Italy, the same kind of underground evolution of the disease is observed during almost two weeks, before a sudden strong growth of the number of confirmed cases, in almost one day.

This day is considered in the calculations as the reference day. Such an evolution is also observed in France, USA, Germany, United-Kingdom and especially in South-Korea where it indicates how easily can the outbreak restart after a full control. The robustness of the outbreak is therefore in question. Likely, this early phase corresponds to inported cases, from people travelling by airplane that can be easily isolated. The effective start of the outbreak is an indication that the disease becomes domestic, and conditions for a local control are becoming much more difficult.

3.1 France

3.1.1 Initial study

The equations have been translated into a Matlab script available in Appendix to analyse the impact of various parameters. Data are obtained from news website reporting official government press conferences. The initial number of contaminated people is taken $N_s\left(t=0\right)=1$, but day 0 is unknown. It is adjusted to have the best fit of initial observed values of $N_s\left(t\right)$. This uncertainty has a wek impact on the overall conclusions. Just absolute numbers may change slightly. From the growth rate of N_s at the early stage of outbreak, $q_{c0} \simeq 0.70$. This means that one sick person can contaminate 4.5 persons in the incubation time so a bit less than one person per day. The french population is taken to $N_{tot} = 6.7 \times 10^{+6}$ inhabitants.

Considering that nothing is done against the outbreak and $q_c\left(t\right) = q_{c0} = 0.70$, the natural last day of the outbreak is 63, all people have been contaminated, and the number of people who died is one million approximately as shown in Fig. 1. The evolution of $q_c\left(t\right)$ is indicated in Fig. 2. The number of very sick people requiring continuous artificial ventilation is exceeding the total number of available respirators in continuing care units 18 days after the beginning of the outbreak, with a maximum of $n_{vsv}^{\max} = 2.7 \times 10^6$, which is dramatically high as compared to operational limits (Fig. 3). Most of the people won't have any respirator, and the risk of death will be likely enhanced.

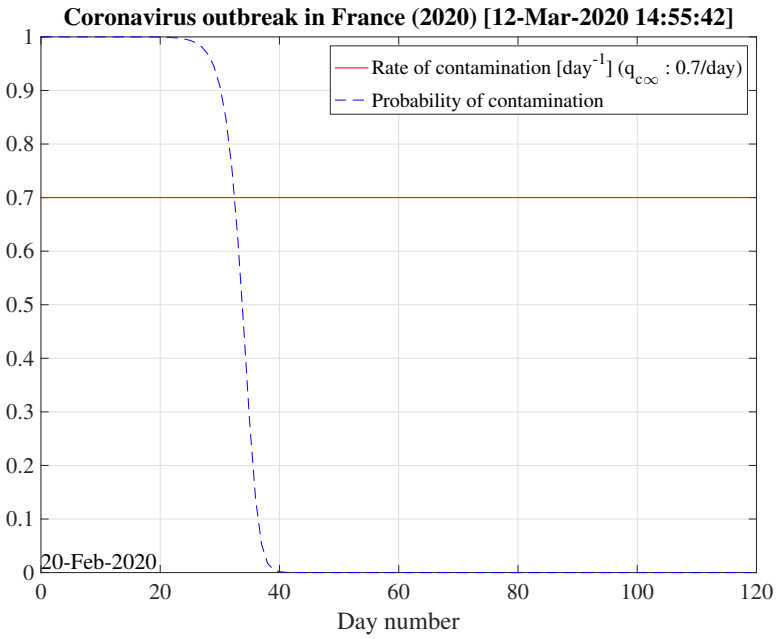

Figure 2: Contamination rate per day and per person and probability of contamination.

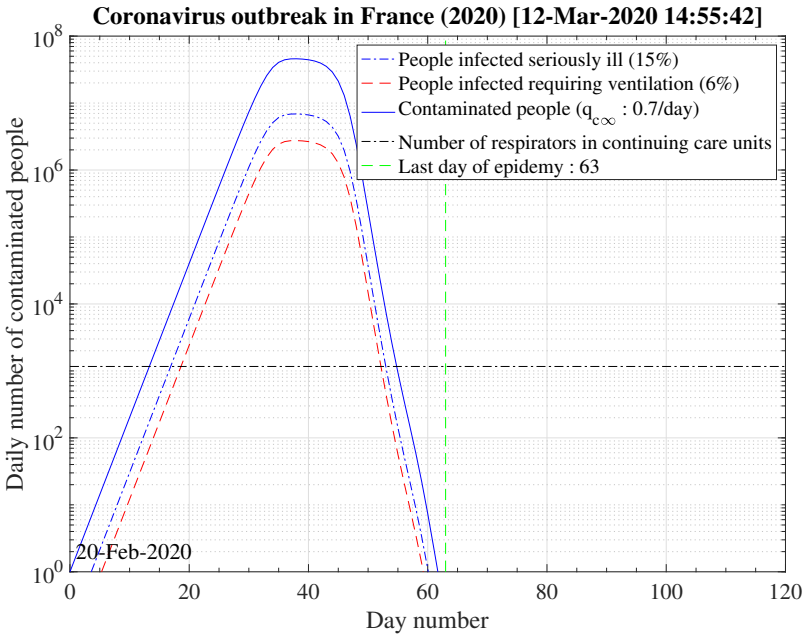

Figure 3: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

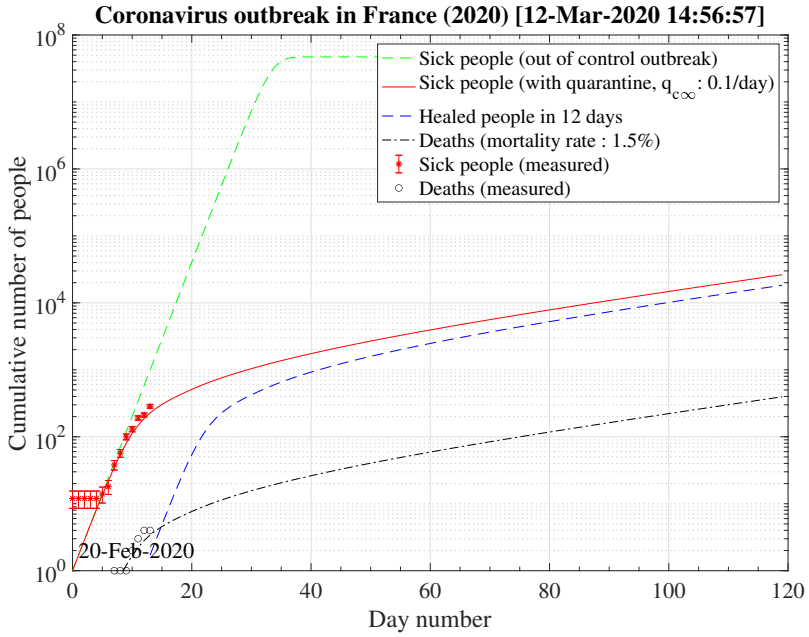

Figure 4: Number of contaminated and dead people by the coronavirus outbreak in France.

Regarding the outbreak status the 4th of March 2020, $q_{c\infty}$ falls down to 0.1 approximately, as shown in Fig. 5, and the outbreak seems under reasonable control as shown in Figs. 4. The last day of the outbreak is 87, and the maximum number of persons that are sick is about 311 (Fig. 6). The number of people requiring ventilation remains always well below the capacity of continuing care units. This case may be easily managed by the country. This results principaly from the setup of a quarantine procedure, by tracking sick people and also people that may have been is close contact to the well identified sick people. Therefore $q_c\,(t)$ is quickly decreasing. This is a critical step for an efficient quarantine, and the possibility to slow down the outbreak. In addition, non contaminated people must reduce themselves the risk of contimation (washing hands periodically, one meter distance minimum, no hand shaking and no kiss, ...), while isolated ones must accept to be in quarantine, for the general interest of the society, especially in countries where individual freedom matters. This acceptance is crucial in the success of the method.

The result is a fast drop of $q_c\,(t)$ leads to the clear inflexion of the cumulative number of sick people, as shown in Fig. 4. The 4th of March, the reduction of the number of contaminations is about 1000 persons, as compared to the case of an uncontrolled outbreak. The number of dead people is also well reproduced by the model.

In the simulation, the drop of $q_c\,(t)$ has been modeled from Eq. 22, with $\tau_{ref} = 10$ days, the sharpness in time of the decrease is reproduced by $\triangle\tau = 2$ days, and the residual value of the contamination rate per day and per person is $q_{c\infty}$. This is an arbitrary number which has a crucial importance on the long term evolution of the outbreak. As shown in Fig. 4, the quarantine leads to a saturation of the number of sick people.

The sensitivity of the model to $q_{c\infty}$ is a critical issue for the control of the outbreak. If it is raised to $q_{c\infty} = 0.15$ as shown in Fig. 8, which is still compatible with observations at the 4th of March 2020, as seen in Fig. 7, the number of contaminated people is increasing up to reach N_{tot}, which means that all the country will be contaminated, but on a much longer time scale as compared to the case without a quarantine. The outbreak is not under control but remains manageable, as shown in Fig. 9, since the growth rate of people that are requiring a respirator is small. Their are some margins to increase the number of respirators in continuing care units. This should be the realistic approach at present time.

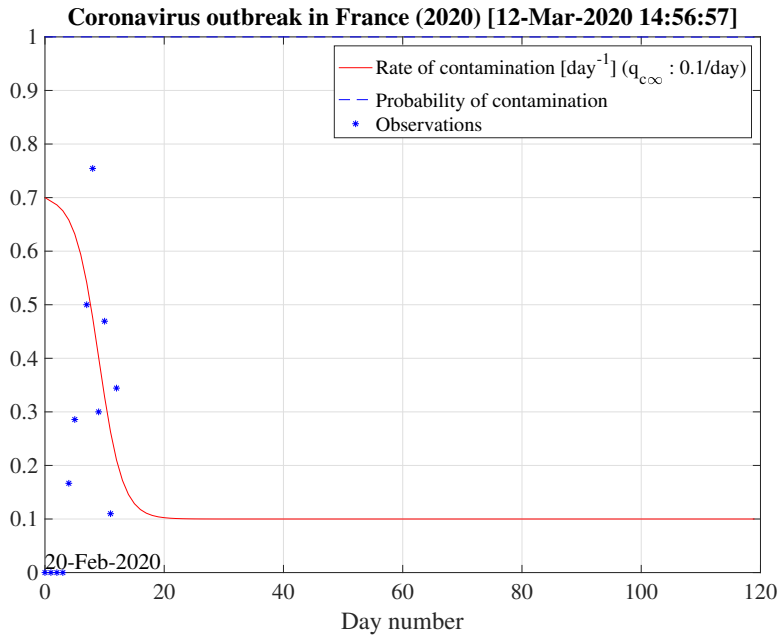

Figure 5: Contamination rate per day and per person and probability of contamination.

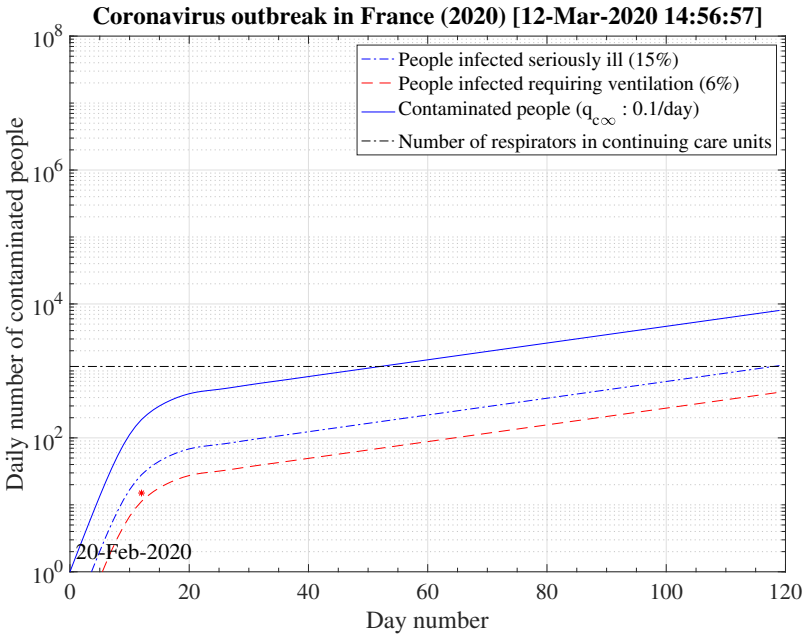

Figure 6: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

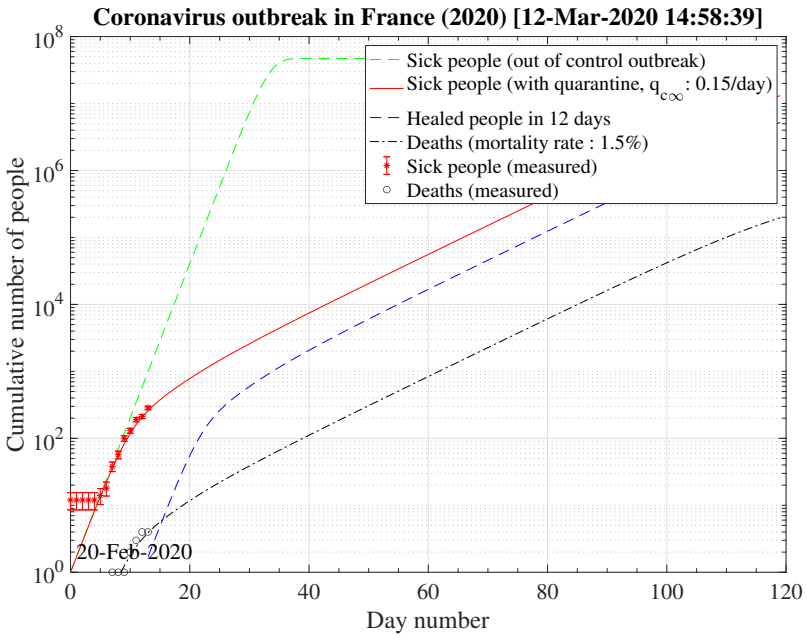

Figure 7: Number of contaminated and dead people by the coronavirus outbreak in France.

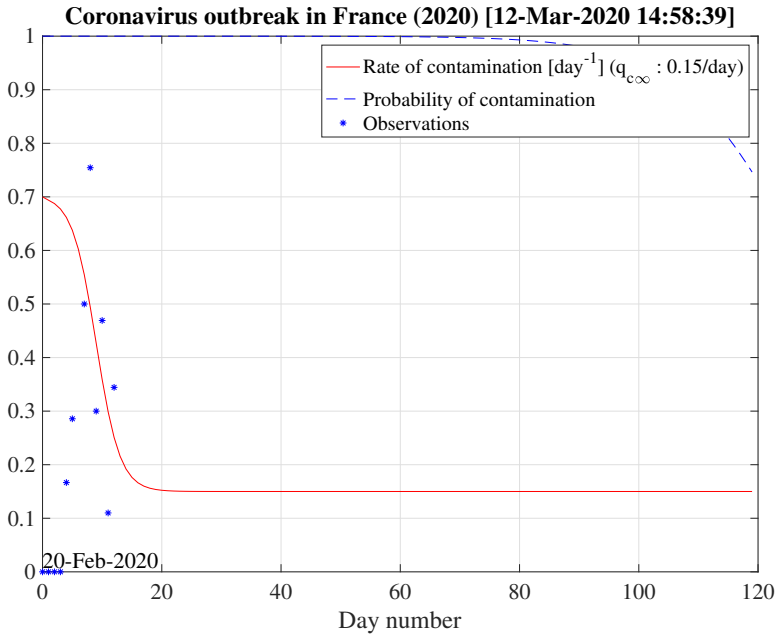

Figure 8: Contamination rate per day and per person and probability of contamination.

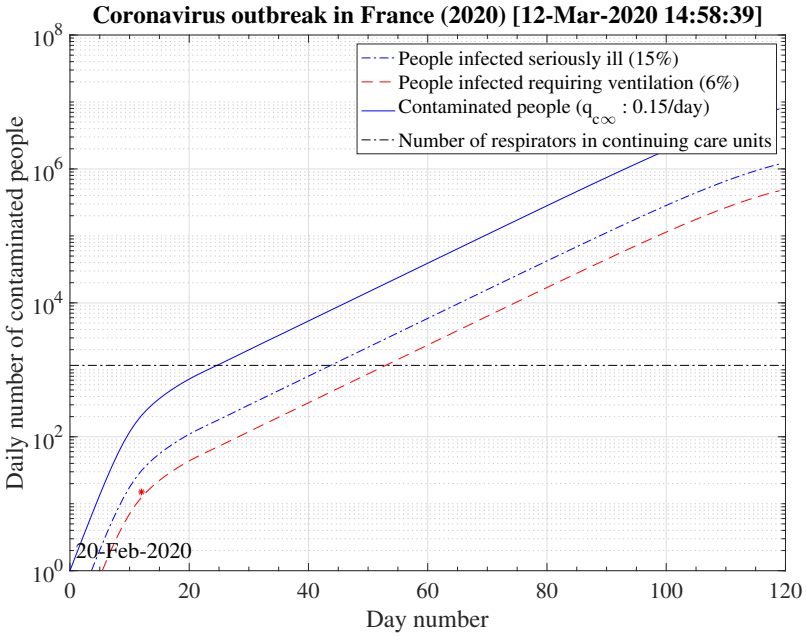

Figure 9: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

3.1.2 Latest analysis (high fatality rate scenario)

Each additional day after the 4th of March give precious details on the effective control of the outbreak, and issues in the coming weeks. Data can be added easily in the script to follow the evolution and understand the outbreak. In particular, the function given by Eq. 22 may have to be changed after a given time if necessary.

The 6th of March, the growth of contaminated people is very important, and is $q_{c\infty} = 0.25$ must be chosen to reproduce observations with the model, a much higher value than initialy estimated the 4th of March. This highlight the impossibility to extrapolate with strong confidence what will be the evolution of the outbreak. Here the model helps just to extrapolate if nothing is done at a given day.

Thanks to the observations, the outbreak is therefore not under control, and will become not manageable 28 days after the beginning of the outbreak, so at the end of March, if nothing is done. The number of sick people will exceed ten thousands after 30 days, so at about the 20th of March. Almost everybody will be concerned and be contaminated in hundred days, and at that time, the number of deaths will reach about 714000. This number should be compared to the number of deaths because of the flue in 2019, which is 8100. So hundred times more..., which illustrates the severity of the outbreak. The end of the outbreak will last in a year approximately.

- **8th of March:** the growth of cases is well predicted by the model without changing any parameter.
- **9th of March:** the growth of confirmed cases is well predicted by the model without changing any parameter, as well as the number of deaths and very severe cases. No parameters changed since 4 days, and the contamination rate remains very high. The level 2 of the outbreak management does not slow down it significantly.
- **10th of March:** the increase of the number of confirmed cases is improving and $q_{c\infty} = 0.29$, which is a clear indication that the outbreak not under any controlled, and even the slowing down is not existing. The government is not telling the truth !
- **11th of March:** the increase of the number of confirmed cases is increasing as predicted by the model. The number of deaths seems to be a bit higher than expected, but the level

is still low, and statistical uncertainty remains large. The number of people requiring very active ventilation is also well predicted and reached about 104 persons now, about $\delta_{vsv} = 6\%$.

- **12th of March:** Nothing as changed. The evolution of the disease is fast, and no slowing down is observed.
- **13th of March**: Nothing as changed concerning the growth rate of the number of confirmed cases and deaths. The model with previously chosen parameters is predicting very well the progression of the disease. Concerning the number of very sick people requiring artificial ventilation in continuous care units, $\delta_{vsv} = 5\,\%$ gives much better results than $\delta = 6\,\%$ previously chosen. The significant number of cases allow to have a better estimate of this coefficient. The other parameters of the model for France are unchanged since 8 days.
- **14th of March**: Nothing as changed concerning the growth rate of the number of confirmed cases and deaths. The country is on the path of what is sais the "herd immunity", namely the worse case.... The number of very sick people requiring artificial ventilation in continuous care units has jumped significantly. Close to the level of the low fatality rate scenario.
- **15th of March**: Same trend. No simulation parameters have been changed. The number of very sick people requiring active continuous ventilation is in line with prediction of the high fatality rate scenario. A faster rise not yet observed (the numbers are more difficult to find) would indicate that the low fatality rate scenario is more favorable.
- **16th of March**: Same trend. $q_{c\infty} = 0.27$ for a better fit. Data and model are shown in Fig. 12 for people in intensive care and deaths. The numerical and analytical values of $\tau_{peak} - \tau_{ref}$ are calculated, and no peak is found as expected. So outbreak evolution tends towards a herd immunity. For better fit of cumulative number of deaths, $\delta_d = 2.5\%$ close to other countries. WARNING : Until 16th of March, the number of cases certified in France and the number of deaths was well correlated by the same law. After the 16th of March, following the change in government doctrine, the adjustment is made preferentially on the number of deaths only, keeping the same percentage of deaths and people in intensive care. It is therefore becoming a "high fatality rate" scenario similar to the low fatality rate scenario (see Sec. 4.2.1), since obviously the number of certified cases is no longer a representative random sampling of the number of real cases, but an indicative biased measurement only. This rule is applied to all countries (keeping unchanged the fatality rate prior to the 16th of March), as there are increasingly marked differences between the number of detected cases which tends to decrease and the number of deaths which is still rising very strongly. When the mortality rate is 0.7% (Cruise liner Diamond-Princess, Switzerland and South-Korea), the standard and non-standard scenarii are identical. If changes are needed to heve a better description of the time series (effect of confinement), the parameters of the simulation are therefore adjusted to follow the number of deaths. Hence, there was no change on the 16th of March in the parameters in France by following the number of deaths.
- **17th of March**: Same trend.
- **18th of March**: Same trend.
- **19th of March**: Same trend.
- **20-26th of March**: Still same trend globally. The threshold of 1000 deaths has been crossed the day it was expected.
- **27th of March**: so sign that the peak is soon coming.
- **28th of March**: Still, no clear sign that the outbreak peak is coming soon.
- **29th of March**: first signs that the outbreak peak is approaching. The day before, there was some weak signs, but today, they seem more clear. Simulation parameters have been slightly changed to $q_{c0} = 0.2704$, $q_{c\infty} = 0.22$, $\tau_{ref} = 10 + 24$ days, $\triangle\tau = 10$ days. The outbreak is still not controlled with $q_{c\infty} = 0.20$.

- **30th of March**: No clear change, and thanks to the noise level of the data, the contamination rate is slightly increased to $q_{c\infty} = 0.22$.
- **31th of March**: Slight slowing down. $q_{c\infty} = 0.20$. But this is not very clear.
- **1st of April**: Slight slowing down. $q_{c\infty} = 0.17$.
- **2nd of April**: International organizations record deaths in nursing homes due to SARS-cov-2. This result in a jump of the daily number of deaths, since this number includes deaths over many days (+886). This can mask the very slow slowing-down trend observed over the past three days. For the moment, the simulation parameters remain unchanged.
- **3nd of April**: Daily number of deaths includes people dead at home or nursery. To remove it will lead to complex accounting of deaths from hospital. There, the total number is kept, and the general trend with time, which is meaningful, will remain likely unchanged. It has been shown for other countries (Iran, Italy). Possibility to include jump because of counting in calculation will be considered.
- **4th of April**: Offset in calculations is considered to account for the cases of nurseries and other health care houses. So there is jump in the calculation that reflects this fact. However, it does not change the general time evolution, with a progressive increasing slowing down. $q_{c\infty} = 0.16$. The daily number of people in intensive care units is decreasing significantly.
- **5th of April**: Incorporation of N_d in Eq.2 . There are serious indications that the peak is now close. The simulations parameters have been modified accordingly, and $q_{c0} = 0.35$, $q_{c\infty} = 0.053$, $\tau_{ref} = 10 + 24$ days, $\triangle\tau = 8$ days. The peak is for the 6th of April (to be confirmed) and 34016 deaths are expected at the end of the outbreak expected after the 120 days of simulations (13th of June). Confirmation is necessary on the coming days, regarding the additional contribution of nurseries.
- **6-8th of April**: Single set of parameters : $q_{c0} = 0.67$, $q_{c\infty} = 0.02$, $\tau_{ref} = 3$ days, $\triangle\tau = 18$ days. Better fit over the whole range.
- **9-15th of April**: $q_{c\infty} = 0.006$ for a better fit. The other parameters are unchanged. This indicates an increasing stabilisation of the outbreak.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

3.1.3 Effect of the residual contamination rate on long term evolution (high fatality rate scenario)

From the high fatality rate scenario, it is possible to evaluate the effect of the reduction of $q_{c\infty}$ from q_{c0} down to 0 on the duration of the outbreak, the day at which the outbreak peaks and the total number of deaths. Initial simulation parameters that are not changing in the scan, are : $q_{c0} = 0.7$, $q_{c\infty} = 0.27$, $\tau_{ref} = 10$ days, $\triangle\tau = 2$ days. Since the amplitude of the outbreak peak depends of the reference day, calculation are performed with a second set of paremeters starting at day 24 (16th of March) at which confinement is decided in France. Initial ones are unchanged, while in the phase, i.e. after day 24, q_{c0} is deduced from continuity of $q_c\,(t)$, $\tau_{ref} = 10$ days and $\triangle\tau = 10$ days, the latter being longer to reflect the longer decay of the outbreak.

As shown in Fig. 15, the duration of the outbreak starts to increase when $q_{c\infty}$ is decreased and exceeds rapidly the the upper limit of 120 days of the study here considered. As far as $q_{c\infty} > 0.05$, the outbreak is not controlled by confinement but naturally controlled by herd immunity. If in the confinement phase $q_{c\infty}$ is divided by more than a factor 5, the outbreak can be controlled, the smaller is $q_{c\infty}$ the shorter is the outbreak. For $q_{c\infty} = 0.05$, the outbreak lasts more than 120 days from the time at which it started (simulation limit).

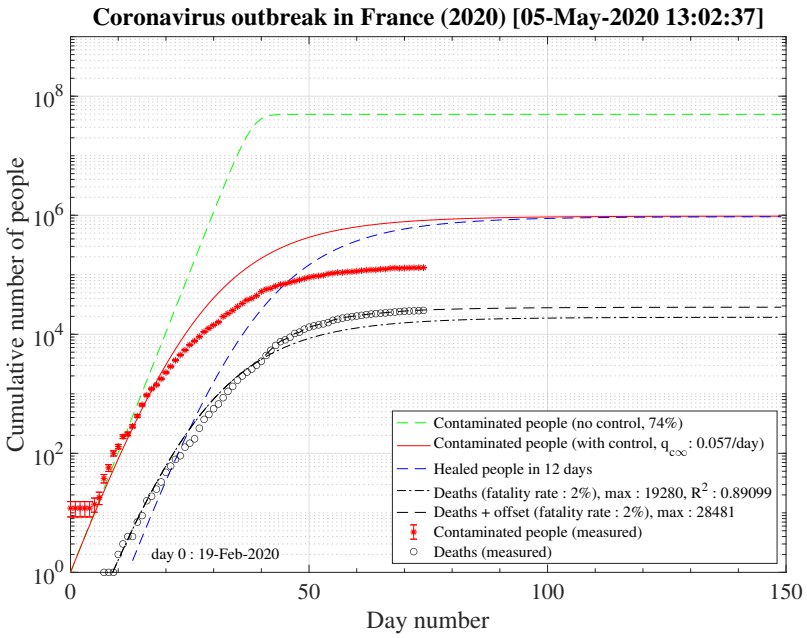

Figure 10: Number of contaminated and dead people by the coronavirus outbreak in France. High fatality rate scenario.

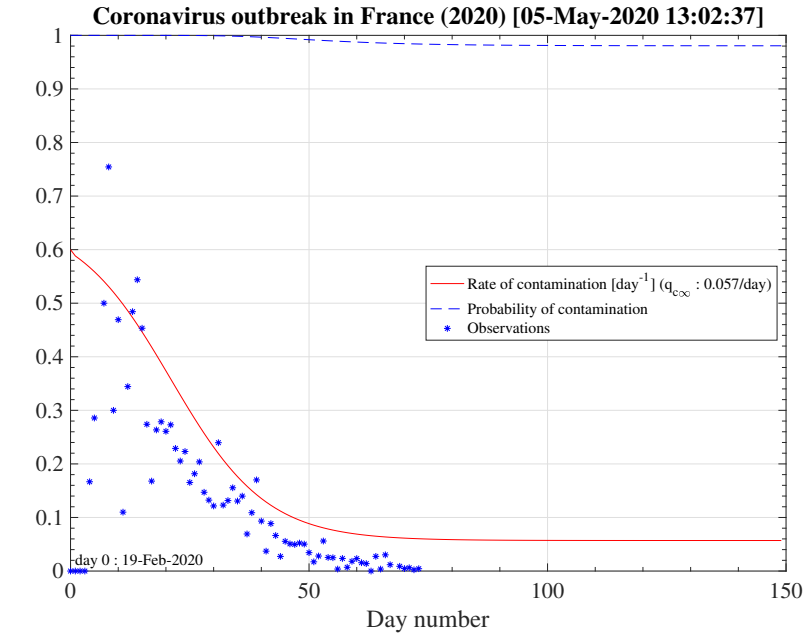

Figure 11: Contamination rate per day and per person and probability of contamination. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

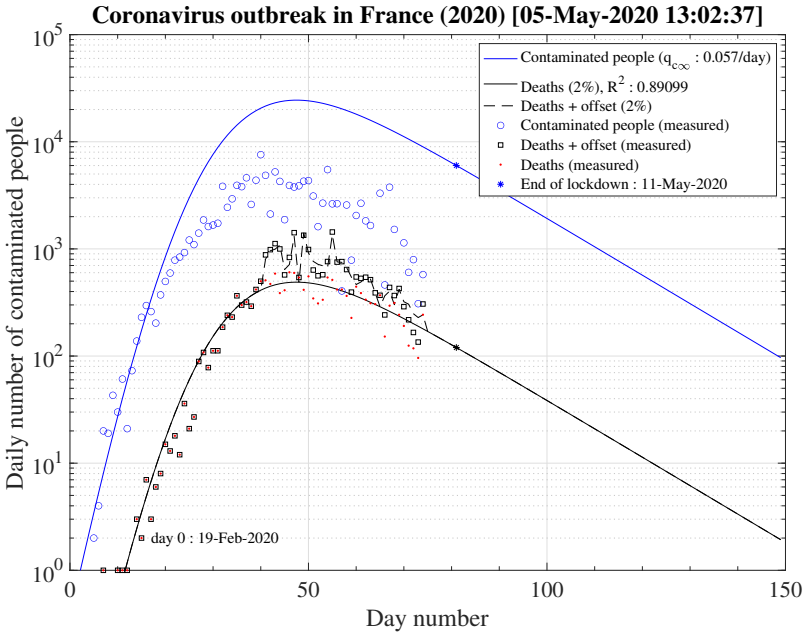

Figure 12: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. High fatality rate scenario.

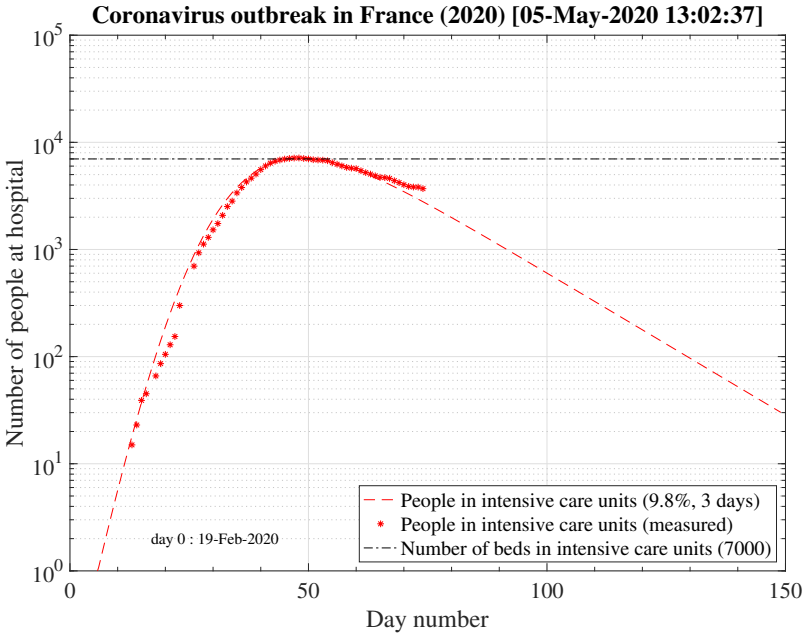

Figure 13: Number of people in intensive care units., fraction of the contaminated people, and additional delay, thanks to recovery time. High fatality rate scenario.

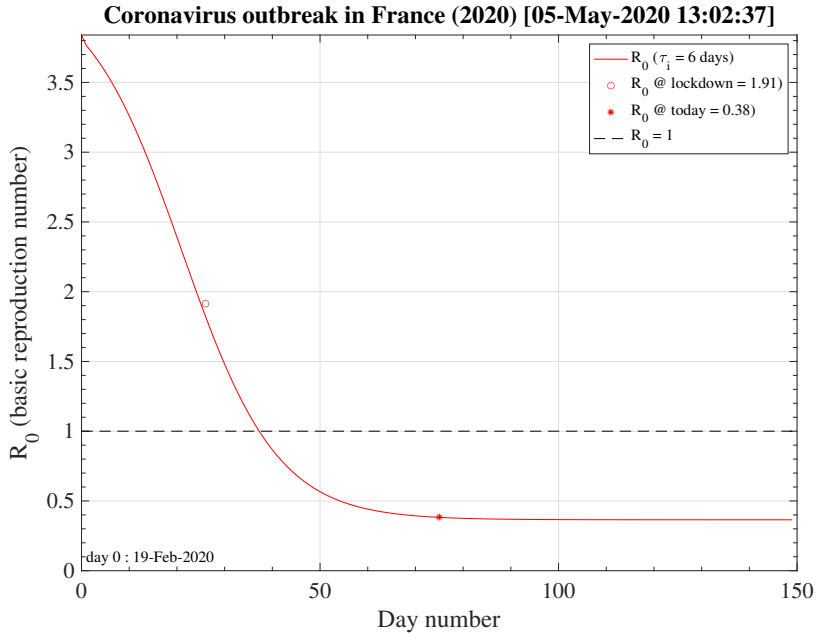

Figure 14: Evolution of the basic reproduction number R_0. High fatality rate scenario.

In Fig. 16, the total number of deaths is shown. For $q_{c\infty} = 0.05$, it is down to 15000 approximately. It rises quickly if the outbreak is not controlled, i.e. $q_{c\infty} > 0.05$.

The time at which the outbreak peaks is shown in Fig. 17. It decreases when $q_{c\infty}$ is lowered, but remains almost independent of $q_{c\infty}$, around 45 days, below $q_{c\infty} = 0.01$. It is 51 for $q_{c\infty} = 0.05$. The analytical estimate where assumptions holds is also shown and is consistent with observations. Finally, in Fig. 18, the outbreak peak is about 15000 if $q_{c\infty} = 0.05$.

This analysis shows explicitely the effort that should be done to reach the objectives of a full control and stop of the outbreak.

3.1.4 Low fatality rate scenario

In this scenario described in Sec. 4.2.1, the reference is the time evolution of the number of deaths N_d and the fatality rate is set to $\delta_d = 0.7\%$ based on the analysis of the outbreak in the line cruiser Diamond Princess and in South-Korea. To reproduce the time evolution of N_d, the simulations parameters are : $q_{c0} = 0.44$ and $q_{c\infty} = 0.32$, and the starting day of the outbreak must be shifted a bit earlier by 6 days as compared to the standard case.

As shown in Fig. 19, the actual number of contaminated people is effectively underestimated, especially after the day 20 corresponding to the change of slope in the official number of positive cases to the coronavirus test (7th of March).

In the low fatality rate scenario, taking $\delta_{vsv} = 2\,\%$, gives the correct level of people requiring an active ventilation in continuous health care units, but the slope does match the observation very well as shown in Fig. 20. Indeed, it is overestimated in the early phase of the outbreak, while it is underestimated later. Such a difference must be followed carefully, because it can be a way to decide which one of the two scenarios is the closest to the observations. Again, time dependence analysis is a critical constraint to assess which model of outbreak is the most likely.

In this scenario, the peak of the outbreak is around 62 days after its beginning, and the number of contaminated people will decrease rapidly in 110 days approximately. But, the number of deaths is very high, around 325000, though much lower to the case if nothing is done and the outbreak evolves freely (collective immunity).

- **5th of April**: Incorporation of N_d in Eq.2. There are serious indications that the peak is now close. The simulations parameters have been modified accordingly, and $q_{c0} = 0.43$, $q_{c\infty} = 0.057$, $\tau_{ref} = 14 + 24$ days, $\triangle\tau = 8$ days. The peak is for the 6th of April (to

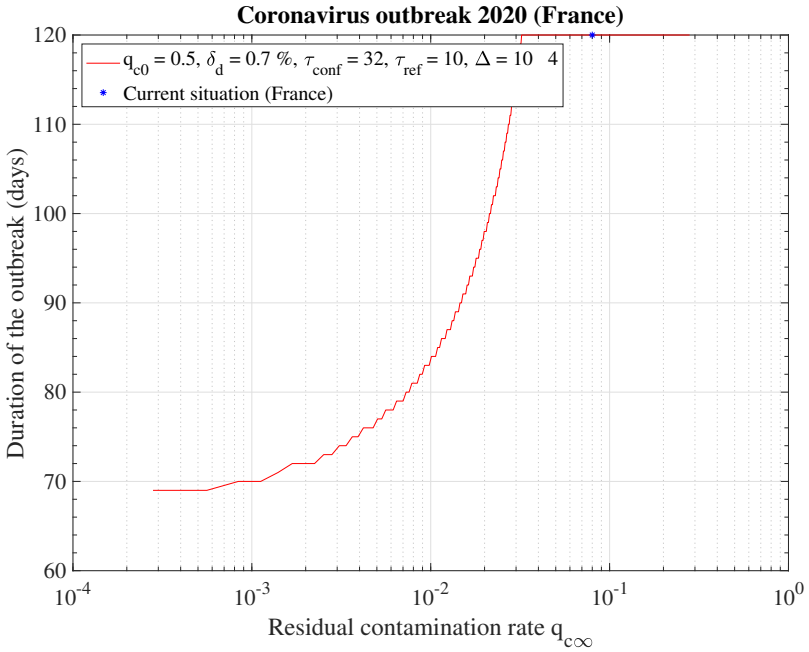

Figure 15: Duration of the coronavirus outbreak in France as a function of the residual contamination rate after the confinement (17th of March). If time evolution of the outbreak corresponds to a residual confinement rate of $q_{c\infty} = 0.01$, the outbreak will last 92 days. Simulation parameters are given in the caption. High fatality rate scenario. The cases above $q_{c\infty} > 0.05$ correspond to herd immunity. The current situation is still hypothetic the 24th of March.

be confirmed) and 28405 deaths are expected at the end of the outbreak expected after the 120 days of siulations (13th of June). Confirmation is necessary on the coming days, regarding the additional contribution of nurseries.

- **6-8th of April**: Single set of parameters : $q_{c0} = 0.44$, $q_{c\infty} = 0.045$, $\tau_{ref} = 37$ days, $\triangle\tau = 8$ days. Better fit over the whole range.
- **9-15th of April**: $q_{c\infty} = 0.035$ for a better fit. The other parameters are unchanged. This indicates an increasing stabilisation of the outbreak.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

3.2 Italy

3.2.1 Initial study

The Italy was the first European country to face a major outbreak of the new coronavirus. During about two weeks, the number of cases was almost constant, likely due to travellers coming from infected countries, which were immediately put in quarantine or at hospital. After the 21st February of 2020, the effective outbreak started quickly, and the country is facing a severe outbreak. All data have been obtained the official WHO website.

Since day 0 is chosen to be the starting point of the outbreak, i.e. when the growth rate of contaminated people starts to become fast. The value $q_{c0} = 3$ is taken to fit the early phase of the outbreak that has a progression like a geometric series as shown in Fig. 23. It is a very high value as compared to France, which indicates the high level of the contamination by the virus per day and per person. The Italian government reacts quite quickly, by setting-up a strong quarantine in concerned areas like in China to fix the outbreak, and $q_c\,(t)$ falls down rapidly to

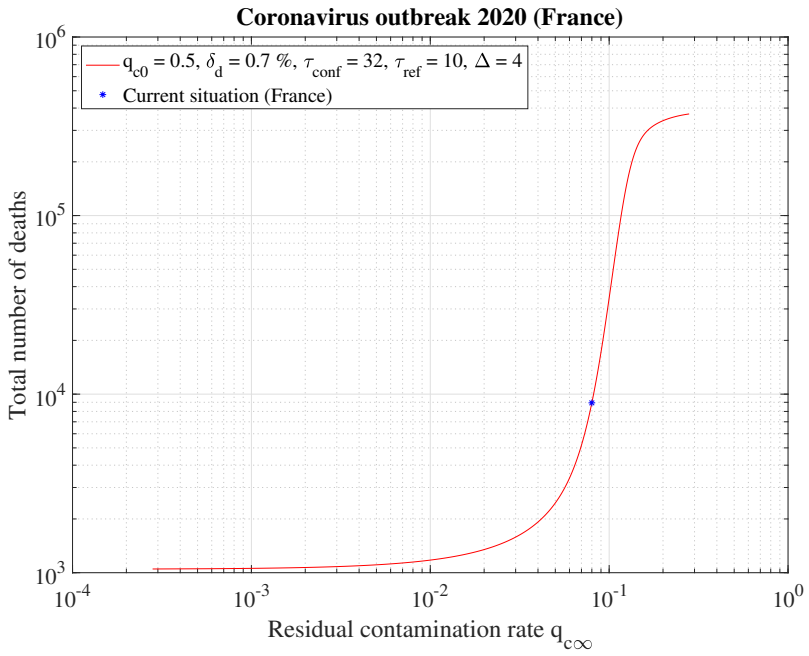

Figure 16: Total number of deaths for the coronavirus outbreak in France as a function of the residual contamination rate after the confinement (17th of March). If time evolution of the outbreak corresponds to a residual confinement rate of $q_{c\infty} = 0.05$, it will reach 15000 approximately. Simulation parameters are given in the caption. High fatality rate scenario. The cases above $q_{c\infty} > 0.05$ correspond to herd immunity. The current situation is still hypothetic the 24th of March.

$q_{c\infty} = 0.2$, with $\tau_{ref} = 3$ and $\triangle\tau = 2.0$, as shown in Fig. 24, and with the evolution of $q_c\,(t)$, the cumulative number of sick people is rather well reproduced, in Fig. 23. Unfortunately, the effort is not enough to contain the outbreak, and the whole population will be contaminated if nothing is done, i.e. a more drastic quarantine with transport restrictions is set-up. Even if $q_{c\infty}$ is France and Italy are close, evolution of the cumulative number of contaminated people is different, because the initial conditions and the type of reaction to control the outbreak have been rather different. Nevertheless, with almost same $q_{c\infty}$, the ultimate result is similar: the outbreak is uncontrolled, like in France, if $q_{c\infty}$ is not drastically lowered, as was reached in China (see Sec. 3.3).

Interestingly, the fatality rate is very high in Italy, $\delta_d = 4\,\%$, comparable to the value in China (see Sec. 3.3), but more than twice the value observed in France. This difference is unclear, and may result either from a difference in the medication that are given to sick people at hospital, or two types of viruses may circulate, with different level of contamination rate.

As shown in Fig. 25, the italian health care will be rapidly overloaded. At day 16 after the beginning of the outbreak here considered, it is already under high pressure as reported by newspaper.

3.2.2 Latest analysis (high fatality rate scenario)

- **8th of March:** The quarantine is decided for North of Italy. The numbers are bad, and a clear bifurcation is observed.

- **10th of March:** The bifurcation observed is just a small jump, but nothing confirms that the quarantine is effective yet. More important is the significant role of the fatality rate to $\delta_d = 6.5\,\%$ the highest level ever seen as the scale of a country. The hospital starts to be saturated. The outbreak remains totally uncontrolled, if numbers remain as they are.

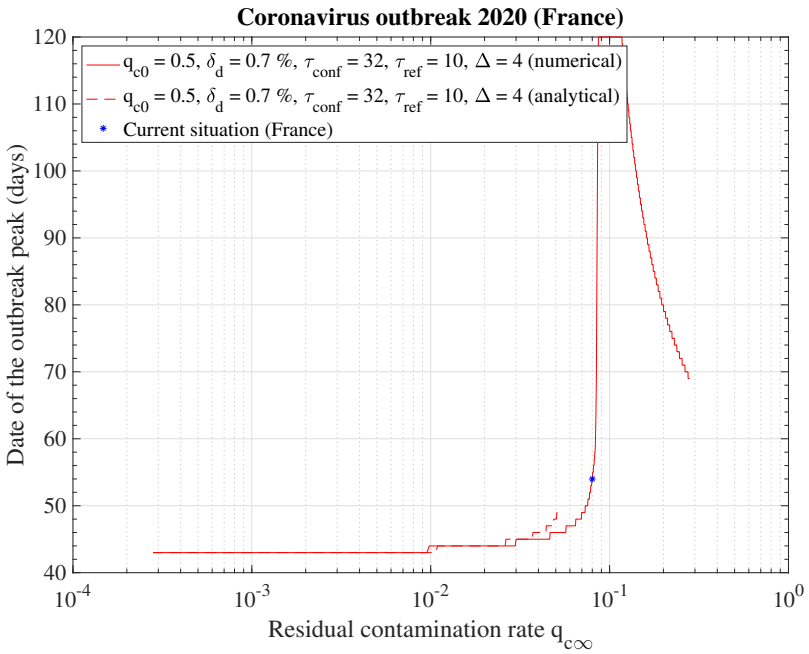

Figure 17: Date of the outbreak peak of the coronavirus outbreak in France as a function of the residual contamination rate after the confinement (17th of March). If time evolution of the outbreak corresponds to a residual confinement rate of $q_{c\infty} = 0.05$, the outbreak peak arises at day 51. Simulation parameters are given in the caption. High fatality rate scenario. The cases above $q_{c\infty} > 0.05$ correspond to herd immunity. The current situation is still hypothetic the 24th of March.

- **11th of March:** the simulations parameters have been slightly modified to have a better consistency between the cumulative number of confirmed cases and the number of deaths. Then $\delta_d = 4.0\,\%$ more consistent with other countries (China, USA), $q_{c0} = 3.2$, $\tau_{ref} = 2$ and $q_{c\infty} = 0.25$. The effects of the quarantine are not yet visible.

- **12th of March:** perhaps a small change of slope thanks to the quarantine, but this must be confirmed in the coming days. The situation is nevertheless totally out of control. The parameters are kept unchanged. The number of deaths seem to increase more than the number of confirmed cases. A sign that the diagnostics are likely becoming very inaccurate, or only a fraction of the contaminated population is diagnosed.

- **13th of March:** it is difficult to see the effect of the quarantine yet. Perhaps a small effect, but no clear change of slope. The residual contamination rate is lowered to $q_{c\infty} = 0.24$ to a better fit, but this marginal. The number of deaths jump from day 17 to 18 and but the slope is unchanged. This may indicate that the reate of mortality in creasing or that the number of confirmed cases is underestimated in the standard approach.

- **14th of March:** Unchanged evolution.

- **15th of March:** Unchanged evolution. The growth of the number of confirmed cases and deaths is in line with predictions. The number of deaths has jumped day 18, but the slope remains similar. The number of very sick people requiring continuous active ventilation is now fully documented. To have a better agreemnt between measured numbers and predctions, $\delta_{vsv} = 8\,\%$, $60\,\%$ higher than in France. The evolution is fairly well reproduced. The outbreak is globally not under control, though first positive effects of people confinement starts to become visible in the Codogno area (Lodi). Data concerning the number of people requiring active and continuous ventilation can been obtained here.

- **16th of March:** Unchanged evolution. Death rate is likely higher than $\delta_d = 4.0\,\%$.

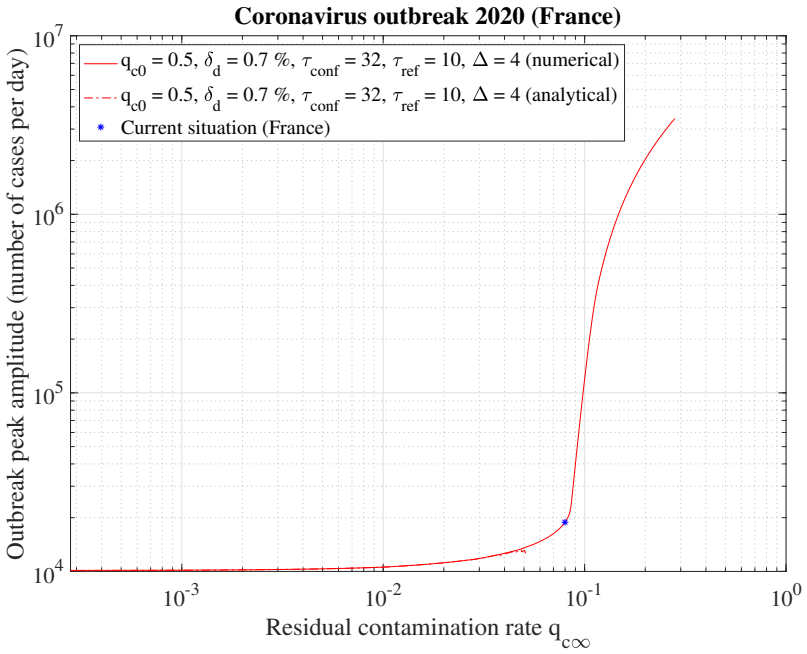

Figure 18: Amplitude of the outbreak peak of the coronavirus outbreak in France as a function of the residual contamination rate after the confinement (17th of March). If time evolution of the outbreak corresponds to a residual confinement rate of $q_{c\infty} = 0.05$, the outbreak peak amplitude is about 15000. Simulation parameters are given in the caption. High fatality rate scenario. The cases above $q_{c\infty} > 0.05$ correspond to herd immunity. The current situation is still hypothetic the 24th of March.

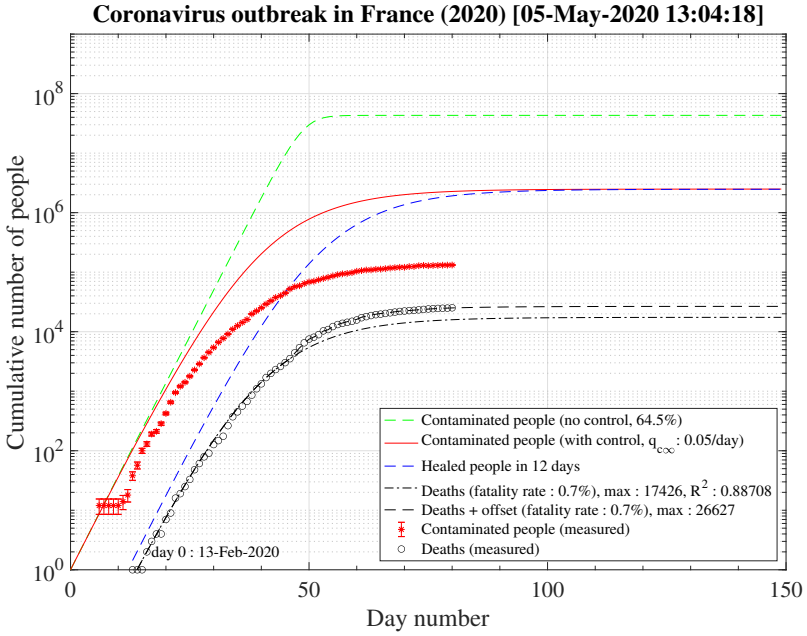

Figure 19: Number of contaminated and dead people by the coronavirus outbreak in France. Low fatality rate scenario.

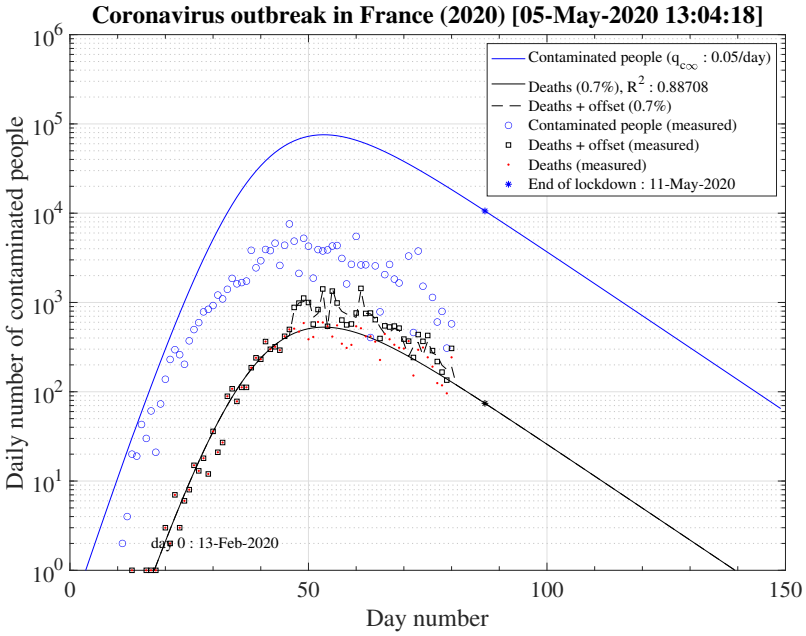

Figure 20: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. Low fatality rate scenario.

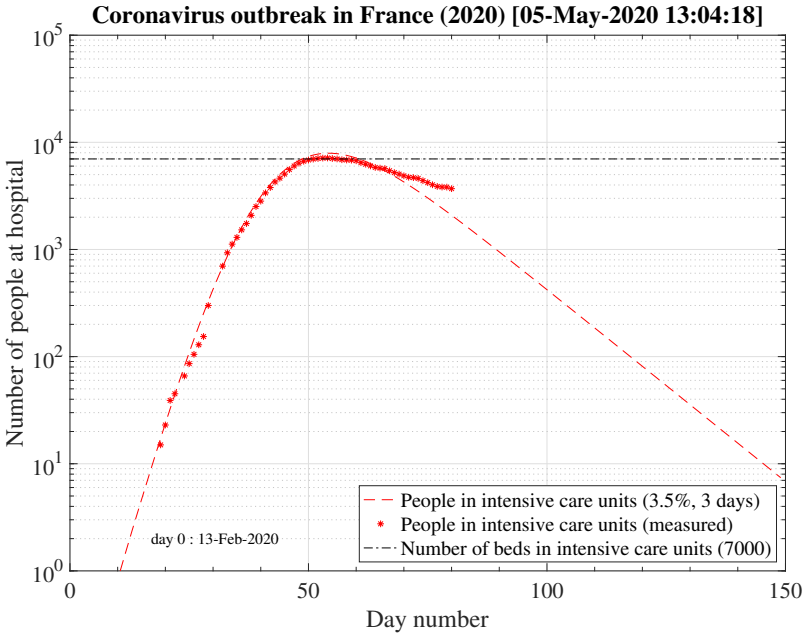

Figure 21: Number of people in intensive care units., fraction of the contaminated people, and additional delay, thanks to recovery time. Low fatality rate scenario.

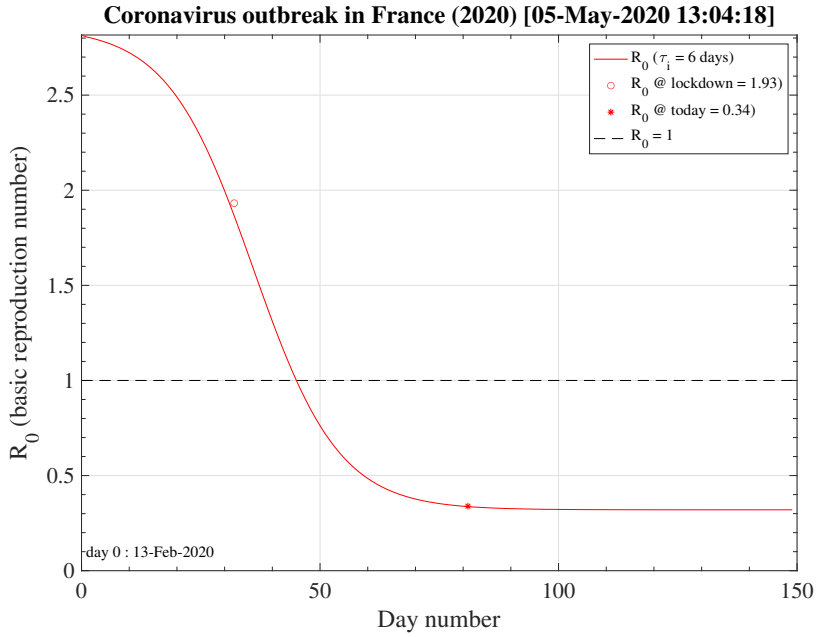

Figure 22: Evolution of the basic reproduction number R_0. Low fatality rate scenario.

- **17th of March:** Unchanged evolution.
- **18th of March:** A possible sign of a very progressive slowing-down of the outbreak, that may indicate first effects of the confinement. More days are necessary to confirm the trend. Nevertheless, the health care situation remains dramatic in some places as reported by private sources.
- **19th of March:** A detailed analysis shows that there is a jump in the number of deaths at day 18, coresponding to the confinement date. After the daily number of death seems to be on a less sharp slope. This is also observed with the number of certified cases, but the robustness of its estimation is questionable. Therefore, at day 18, the simulation parameters have been modified to be more consistent with the number of death, keeping the same fatality rate. They are $q_{c0} = 0.33$, $\tau_{ref} = 6$, $\triangle\tau = 10$ and $q_{c\infty} = 0.1$. The jump is described by a larger valueof $q_c\,(t)$ than it should be to have continuity at day 18, almost twice more, but after $q_{c\infty}$ is divided by 2.5, which may be the first sign of the effects of confinement. If this is confirmed, the outbreak should peak at around day 107 (7th of June 2020) with a very slow decrease after. This analysis must be confirmed by further results in the coming days. The threashold of 10000 deaths is estimated to the 31th of March 2020.
- **20th of March:** The trend towards a progressive stabilization of the outbreak is confirmed. More days will give a better picture.
- **21-23th of March:** The previous trend is confirmed, and best fit is obtained with $q_{c\infty} = 0.05$, so the peak of the outbreak is expected to be around the 6th of April 2020. Evolutions of the outbreak as function of $q_{c\infty}$, from the confinement decided the 8th of March, are shown in Figs. 28, 29 30, 31.
- **24-26th of March:** The previous trend is fully confirmed, and best fit is obtained with lower $q_{c\infty} = 0.03$, so the peak of the outbreak is expected to be earlier, around the 2th of April 2020.
- **27th of March:** The peak is almost reached. Some days must be considered before the decrease. About $20000 - 23000$ deaths may be expected if the effort is maintained. The residual cntaminatio rate is set to $q_{c\infty} = 0.01$ for a slightly better fit.

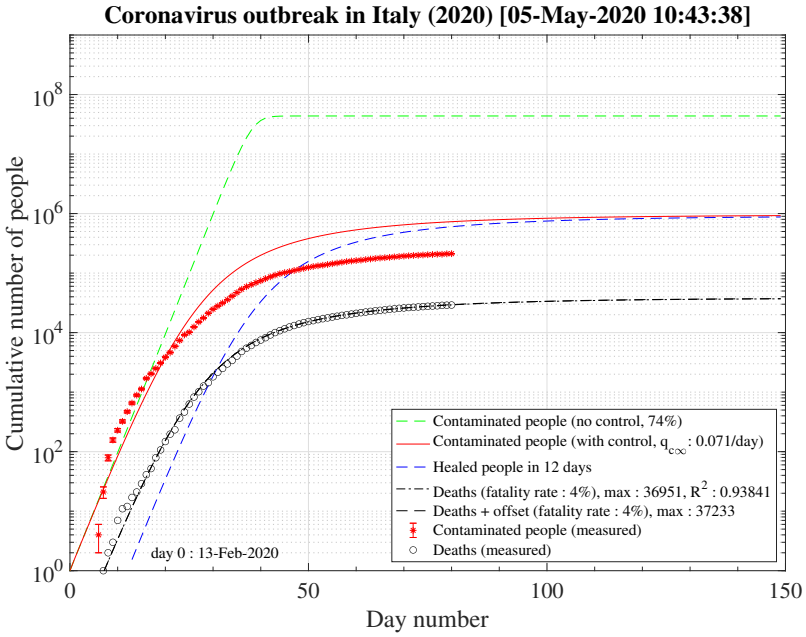

Figure 23: Number of contaminated and dead people by the coronavirus outbreak in Italy. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

- **28th of March:** The data are consistent with the fact that the peak is effectively reached.
- **29th of March:** The peak is reached, and the number of deaths is accurately predicted by 0.2 %. The predicted total number of deaths is ranging between 19000 and 20000, depending of the high or low mortality rates.
- **30th of March**: the peak is passed. The decrease of the daily number of deaths has started. More days will give a clearer picture on he total number of deaths.
- **31th of March**: the peak is effectively passed. The end of the outbreak is estimated by end of May. But this may evolve with time. This just an estimate, consistent with Chinese outbreak control.
- **1st-4th of April**: Confirmation that the peak is effectively passed. No change in the simulation parameters.
- **5-9th of April**: Incorporation of N_d in Eq.2. $q_{c0} = 0.35$, $\tau_{ref} = 18 + 6$, $\triangle\tau = 10$ and $q_{c\infty} = 0.025$. Good fit.
- **10-15th of April**: Single set of parameters to maintain simplicity and the spirit of the model. The two sequences of parameters is reserved to a restart of the outbreak like in USA, South-Korea. The new parameters are $q_{c0} = 0.6$, $\tau_{ref} = 23$, $\triangle\tau = 10$ and $q_{c\infty} = 0.047$. Good fit and same conclusions.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

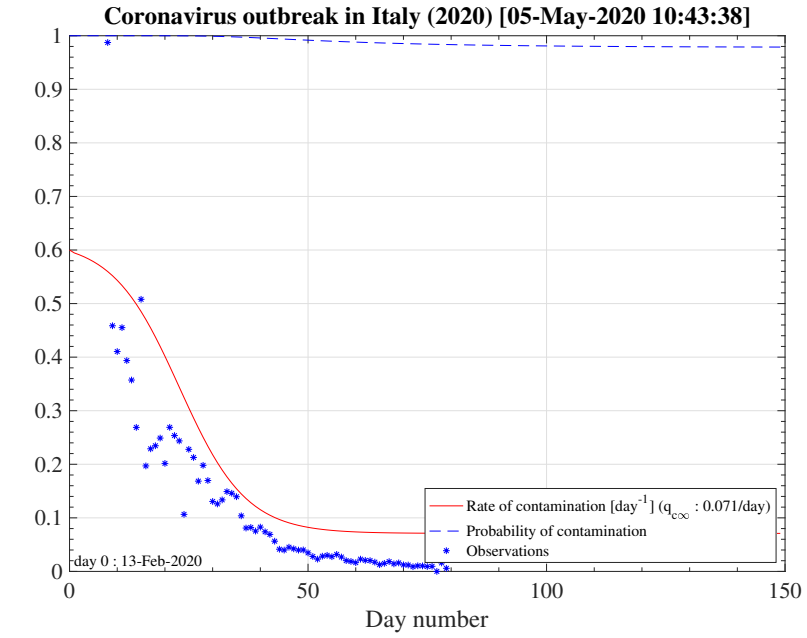

Figure 24: Contamination rate per day and per person and probability of contamination. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

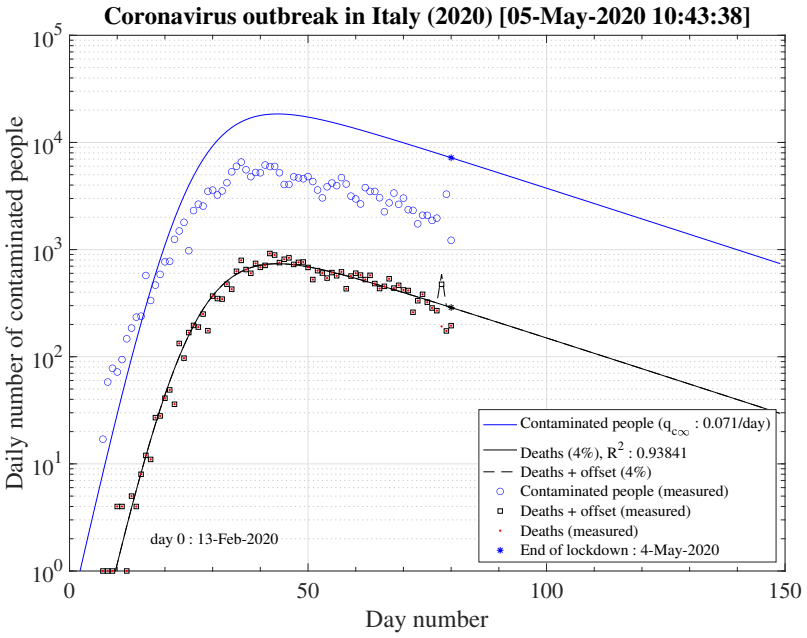

Figure 25: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

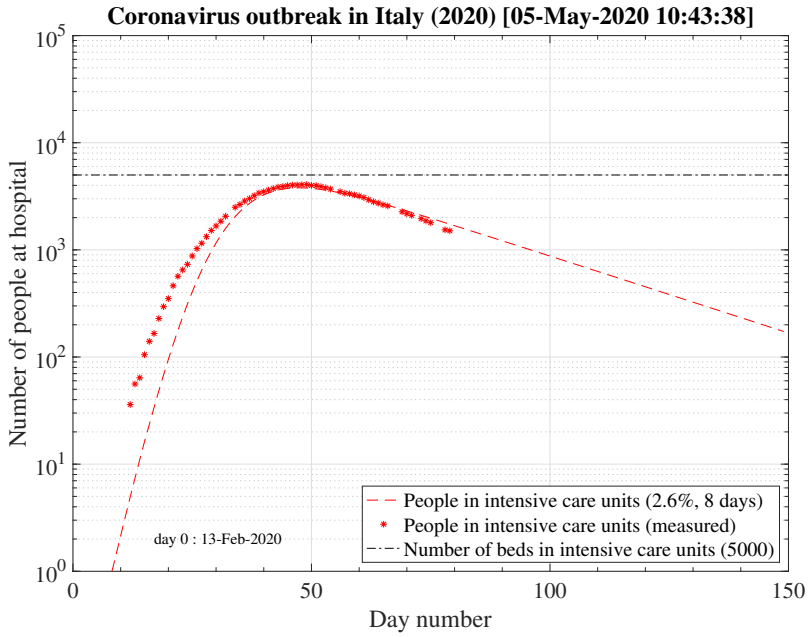

Figure 26: Number of people in intensive care units, fraction of the contaminated people, and additional delay, thanks to recovery time. High fatality rate scenario.

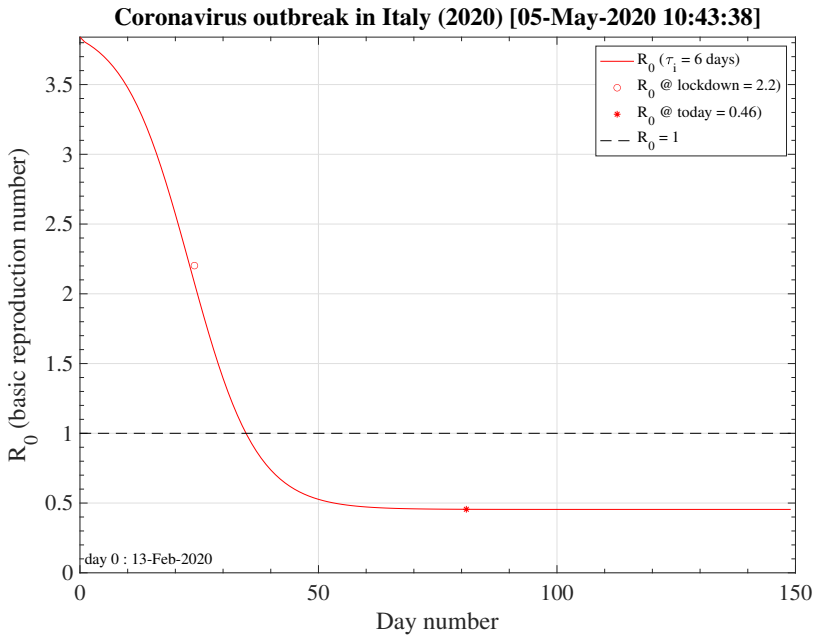

Figure 27: Evolution of the basic reproduction number R_0. High fatality rate scenario.

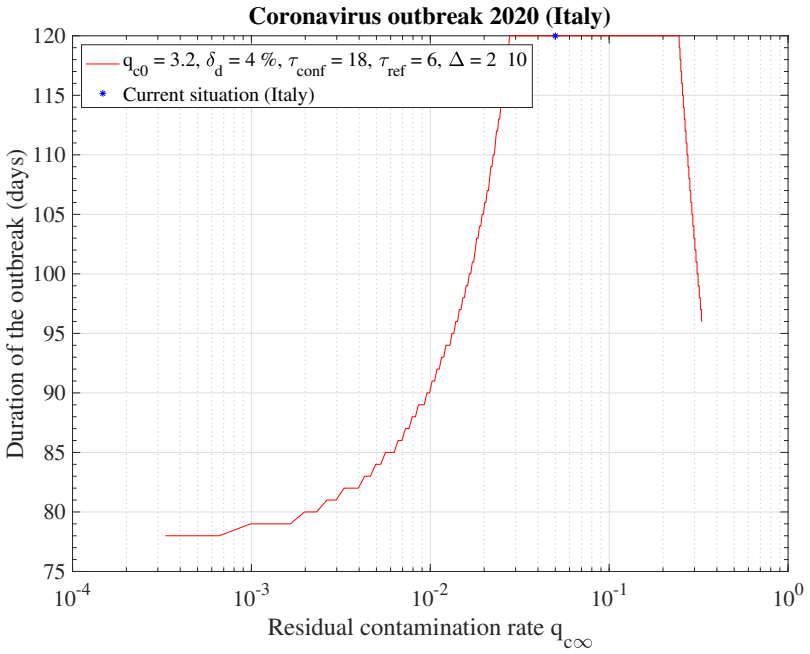

Figure 28: Duration of the coronavirus outbreak in Italye as a function of the residual contamination rate after the confinement (8th of March). If time evolution of the outbreak corresponds to a residual confinement rate of $q_{c\infty} = 0.05$, the outbreak will last more than 120 days. Simulation parameters are given in the caption. High fatality rate scenario. The cases above $q_{c\infty} > 0.05$ correspond to herd immunity.

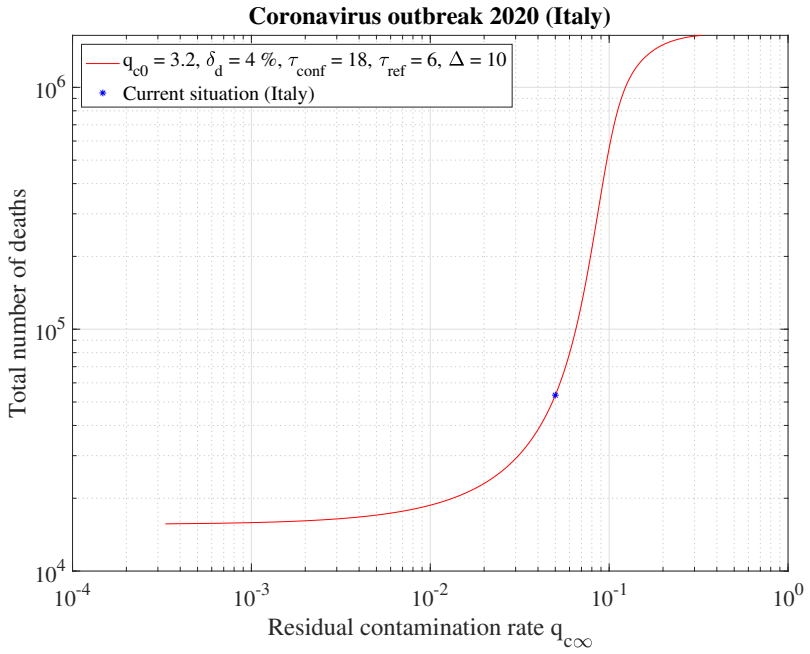

Figure 29: Total number of deaths for the coronavirus outbreak in Italy as a function of the residual contamination rate after the confinement (8th of March). If time evolution of the outbreak corresponds to a residual confinement rate of $q_{c\infty} = 0.05$, it will reach 55000 approximately. Simulation parameters are given in the caption. High fatality rate scenario. The cases above $q_{c\infty} > 0.05$ correspond to herd immunity.

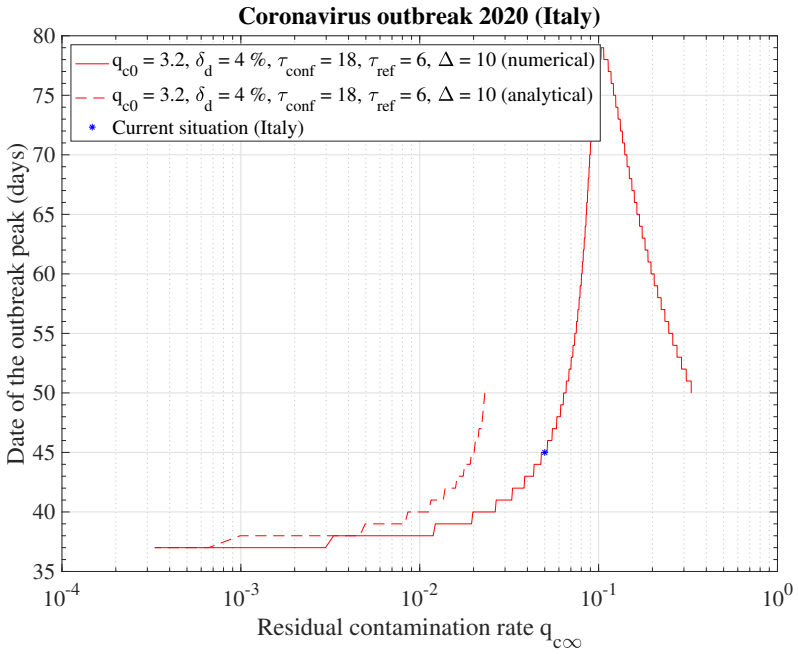

Figure 30: Date of the outbreak peak of the coronavirus outbreak in Italy as a function of the residual contamination rate after the confinement (8th of March). If time evolution of the outbreak corresponds to a residual confinement rate of $q_{c\infty} = 0.05$, the outbreak peak arises at day 45. Simulation parameters are given in the caption. High fatality rate scenario. The cases above $q_{c\infty} > 0.05$ correspond to herd immunity.

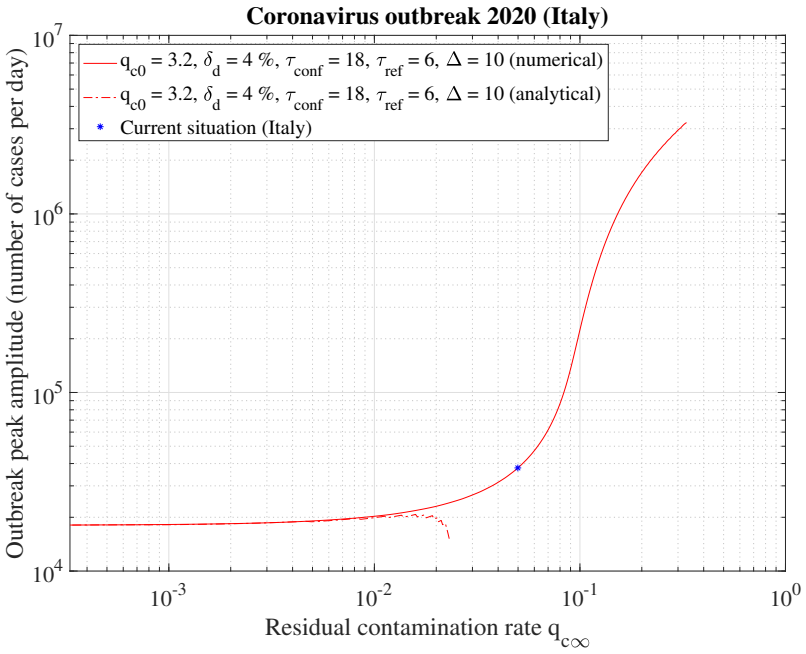

Figure 31: Amplitude of the outbreak peak of the coronavirus outbreak in Italy as a function of the residual contamination rate after the confinement (8th of March). If time evolution of the outbreak corresponds to a residual confinement rate of $q_{c\infty} = 0.05$, the outbreak peak amplitude is about 38000. Simulation parameters are given in the caption. High fatality rate scenario. The cases above $q_{c\infty} > 0.05$ correspond to herd immunity.

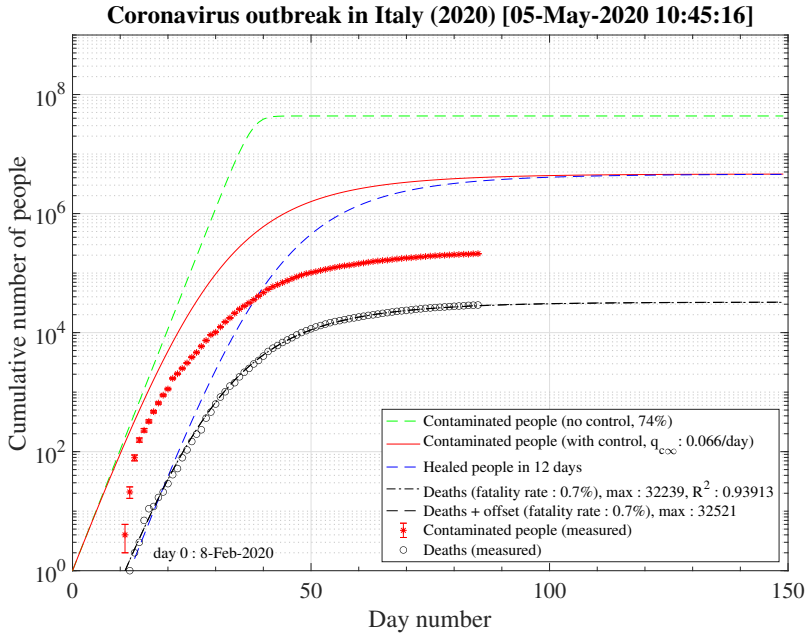

Figure 32: Number of contaminated and dead people by the coronavirus outbreak in Italy. Low fatality rate scenario.

3.2.3 Low fatality rate scenario

The non-standard case applied for Italy is interesting when precursors of the outbreak peak is coming. In order to fit the number of deaths with time (cumulative or daily), the two phases must be considered: before the confinament date and after. First, to reproduced the amplitude of the number of deaths, the reference date must be shifted by three days to the 18th of February. The confinement date is of course unchanged. For the first phase, simulation parameters are $q_{c0} = 3.2$, $\tau_{ref} = 2$, $\triangle\tau = 2$ and $q_{c\infty} = 0.32$. After day 21, they are $q_{c0} = 0.35$, $\tau_{ref} = 6$, $\triangle\tau = 10$ and $q_{c\infty} = 0.01$. Consequently, the outbreak exhibist a peak, around the 2nd of April (a little bit earlier than for the high fatality rate scenario, 4 days), but the total number of deaths is decreased to 20000 approximately. The end of the outbreak is estimated by end of May, while it is much longer for the high fatality rate scenario (one month more at least). So from the two scenarii, it is possible to estimate the total number of deaths in the interval $20000 - 55000$ deaths. The date of the outbreak peak which is robust within 4 days, should occur in the first week of April. All details are available in Figs. 3233.

- **5-9th of April**: Incorporation of N_d in Eq.2. $q_{c0} = 0.35$, $\tau_{ref} = 21 + 6$, $\triangle\tau = 10$ and $q_{c\infty} = 0.01$.

- **10-15th of April**: Single set of parameters to maintain simplicity and the spirit of the model. The two sequences of parameters is reserved to a restart of the outbreak like in USA, South-Korea. The new parameters are $q_{c0} = 0.6$, $\tau_{ref} = 26$, $\triangle\tau = 10$ and $q_{c\infty} = 0.055$. Good fit and same conclusions.

- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

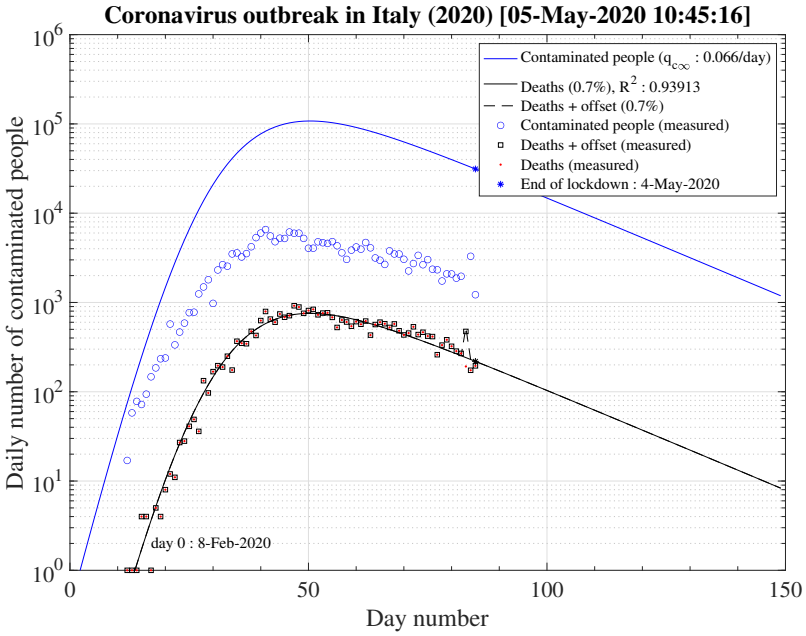

Figure 33: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. Low fatality rate scenario.

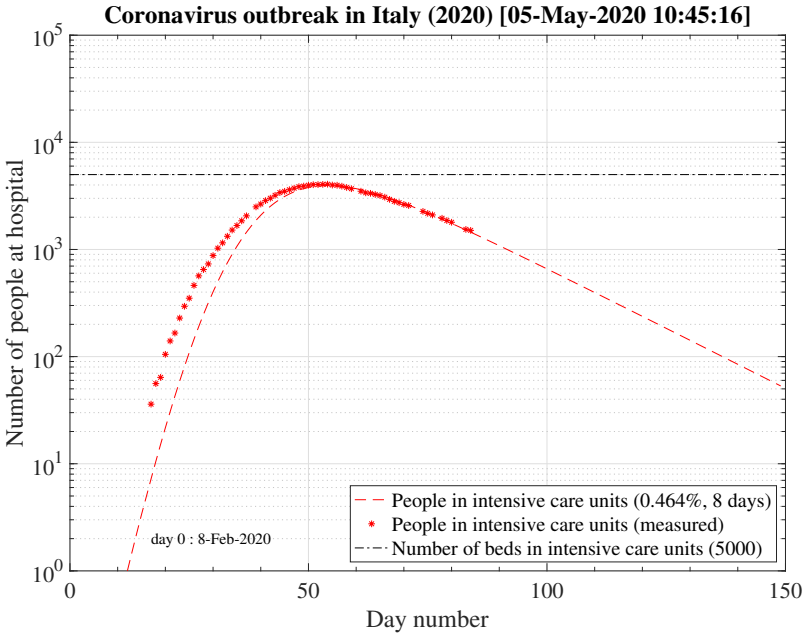

Figure 34: Number of people in intensive care units, fraction of the contaminated people, and additional delay, thanks to recovery time. Low fatality rate scenario.

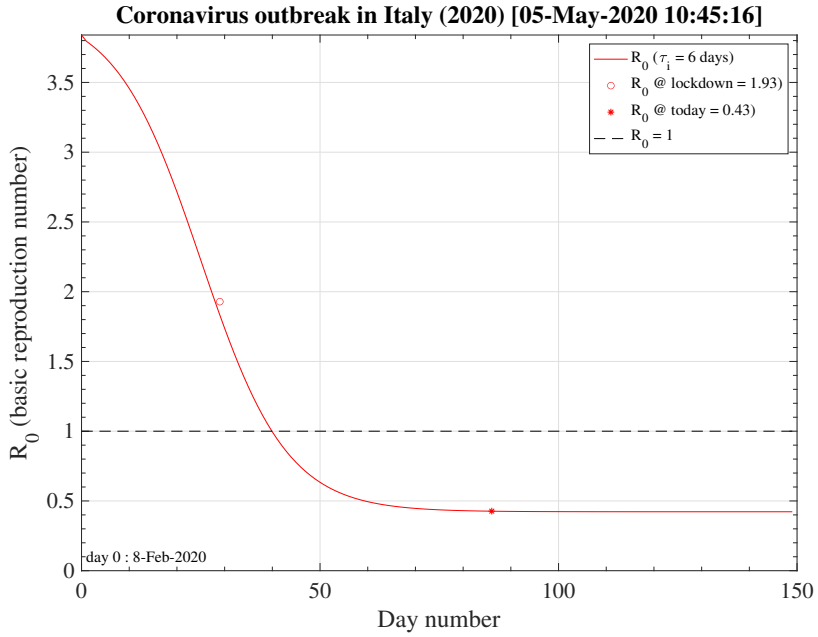

Figure 35: Evolution of the basic reproduction number R_0. Low fatality rate scenario.

3.3 China

3.3.1 Initial study

The outbreak in China started in December 2019, but reports on quantitative data started the 21st of January 2020. They can obtained from the official WHO website. Since day 0 is unkown, it is adjusted with the q_{c0} to fit the early phase of the outbreak that has a progression like a geometric series. It is taken 8 days before the first report, so the 13rd of January 2020. In order to reproduce the very fast growth rate $q_{c0} = 1.41$ is considered and a good agreement is found with observations (see Fig. 36). The couple made by q_{c0} and the initial time has an impact of the saturation of the outbreak, if $q_{c\infty}$ can be low enough. Thanks to their strong quarantine policy, it falls down to $q_{c\infty} = 0.001$, with $\tau_{ref} = 9$ and $\triangle\tau = 5.5$, as shown in Fig. 37, and with the evolution of $q_c(t)$, the cumulative number of sick people is rather well reproduced, in particular in the asymptotic phase, though the exact level is very sensitive to the couple of parameters $(q_{c0}, q_{c\infty})$. At the intermediate phase, at time $t = 20$, the model seems to overestimate the cumulative number of sick people, but it can result from the difficulty to rigorously evaluate the effective number of contaminated people. From the model, China is close to the end of the outbreak, a succes that is only the consequence of an exceptionnal quarantine. The last day of the outbreak is 54.

In order to reproduce the cumulative number of people who died from the virus, a mortility of 4 % must be applied, close to the value for Italy. Seems to be much larger than in France, which is only 1.5 %. This may result from the use of advanced medication, still an open question. Finally the calculated daily number of contaminated people, and those very sick requiring or not an artificial ventilation is given in Fig. 38.

3.3.2 Latest analysis (high fatality rate scenario)

- **8th of March**: stabilisation of outbreak is confirmed.

- **9th of March:** for a better time evolution of the number of contaminated people in China with time, $\tau_h = 14$ gives better evolution. Applied to France, Italy and Switzerland, its has almost no impact on the results and comparison with observations. It gives the end of the outbreak around 70 days after its beginning so around end of March.

- **10th of March:** the progressive stabilization of the outbreak is confirmed by a lower number of contaminated cases and deaths.
- The evolution of the number of deaths is also better, but much less in the middl of the outbreak than at the end. To understand this discrepancy, ones can guess that the rate of mortility is a function of time. It should increase from 2 % to 4 %. The numbers given to WHO may also have been underestimated. In any case, the actual number seems to be stationary, and consistent with the number of confirmed cases.
- **11th of March:** the progressive stabilization of the outbreak is confirmed by a lower number of contaminated cases and deaths.
- **12th of March:** the progressive stabilization of the outbreak is still confirmed by a lower number of contaminated cases and deaths.
- **13th of March:** Nothing has changed in the simulation parameters, and the outbreak is slowing-down progressively.
- **15th of March:** Unchanged evolution. Stabilization is confirmed
- **16th of March:** Unchanged evolution. Stabilization is confirmed. Simulation parameters have been changed to better description of the post-peak phase: $q_{c0} = 1.29$, $q_{c\infty} = 0.02$, while $\tau_{ref} = 9$ and $\triangle\tau = 5.5$ re unchanged. Peak for daily deaths is not well described.
- **17th of March:** Unchanged evolution.
- **18th of March:** The fatality rate has been increased to 2.5 %. for a better fit of observations.
- **19th of March:** Unchanged evolution.
- **20th of March:** Unchanged evolution.
- **21-26th of March:** Unchanged evolution. But the number of certified cases clearly restarts again, which indicates external contamination by travellers. This highlights the risk of a restart of the outbreak. The number of deaths is still decreasing.
- **27-29th of March**: same problem as days before. Borders will be closed the 28th of March to stop external certified cases entering the country. As expected by analysing the fragility of the health situation no herd immunity).
- **30-31th of March**: No change, the daily number of contaminated people and deaths is increasing.
- **1st-3rd of April**: No change, the daily number of contaminated people and deaths is increasing.
- **4-5th of April**: The daily number of contaminated people and deaths seems to decrease. Effect of border lockdown ?
- **6th of April:** Incorporation of N_d in Eq.2. If one consider consistently that only the number of deaths matters, then $q_{c0} = 1.29$, $q_{c\infty} = 0.015$, while $\tau_{ref} = 2$ and $\triangle\tau = 8.0$. It is interesting, in that case to see that the outbreak is not ended, and during a long period, the daily number of certified cases is underdetermined. This may give an explanation of the decreasing level of certified cases. A slight change in $q_{c\infty}$ may lead to the better observed total number of deaths, but its absolute value is not necessarily a reference.
- **7-15th of April**: Incorporation of N_d in Eq.2. $q_{c0} = 1.2$, $\tau_{ref} = 2$, $\triangle\tau = 8$ and $q_{c\infty} = 0.05$. Good fit of deaths.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.
- **17th of April**: jump in the number of deaths (1290) and case (325) at Wuhan that were forgotten.

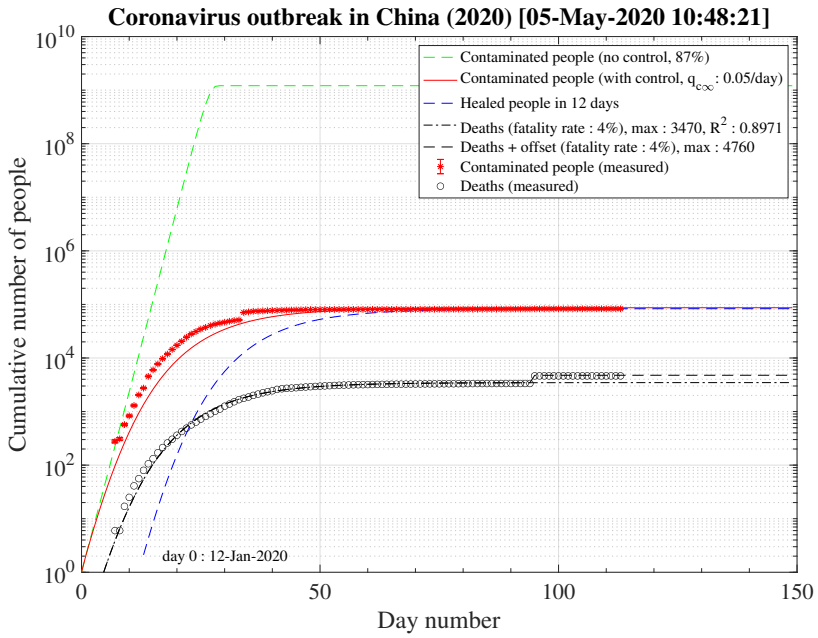

Figure 36: Number of contaminated and dead people by the coronavirus outbreak in China.

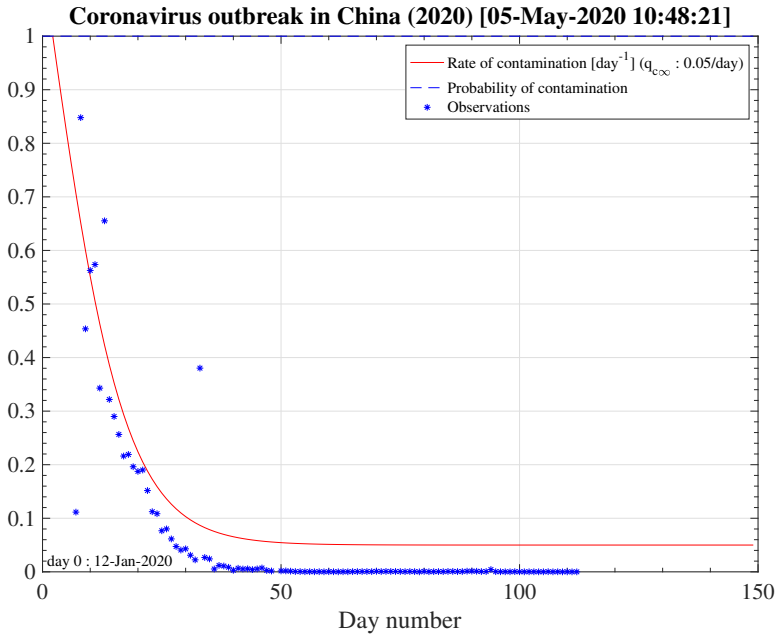

Figure 37: Contamination rate per day and per person and probability of contamination.

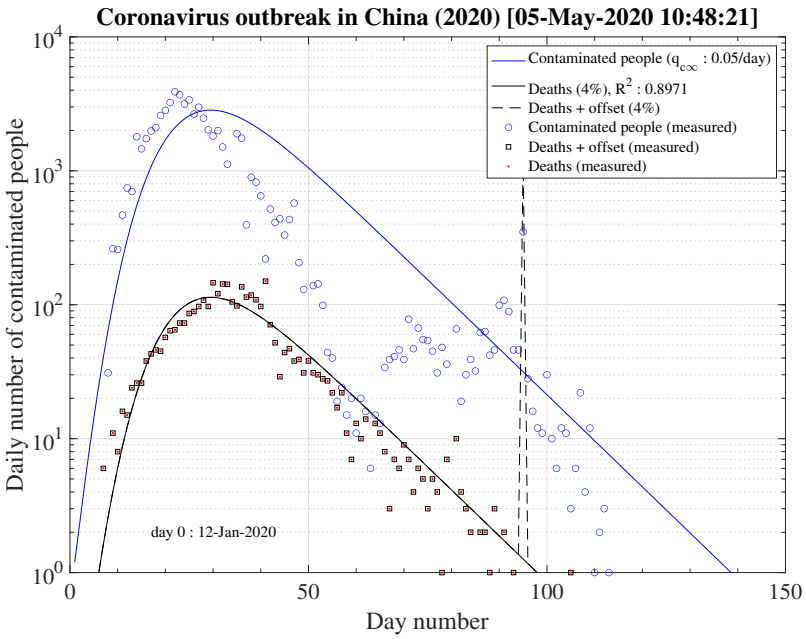

Figure 38: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

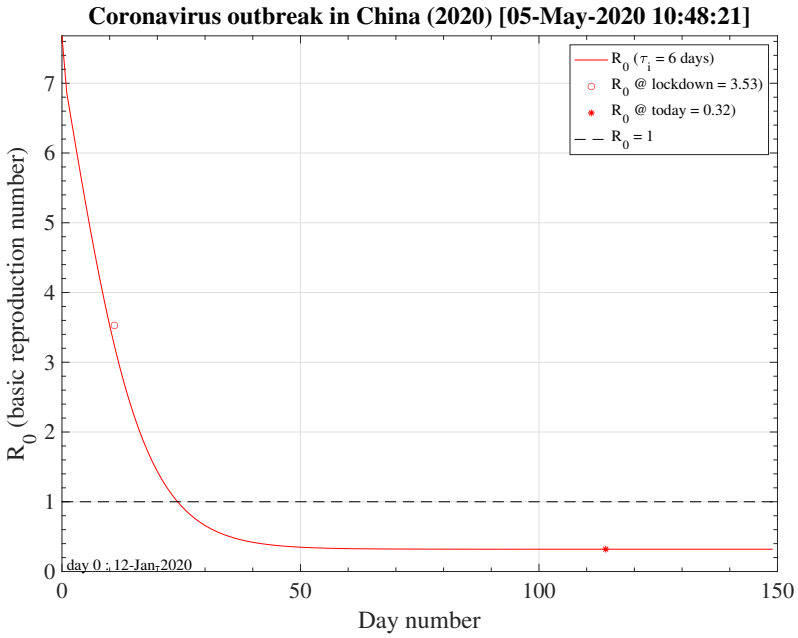

Figure 39: Evolution of the basic reproduction number R_0. High fatality rate scenario.

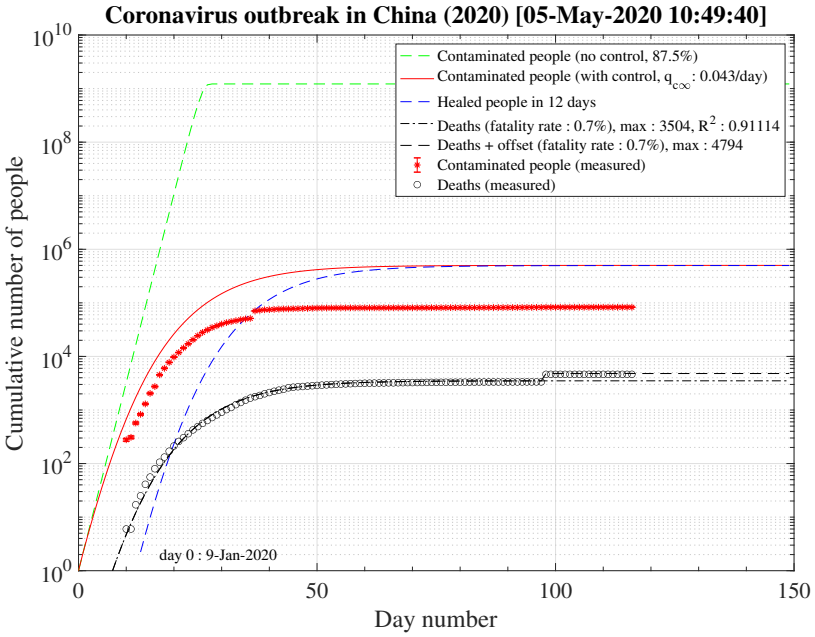

Figure 40: Number of contaminated and dead people by the coronavirus outbreak in China.

3.3.3 Latest analysis (low fatality rate scenario)

- **6th of April:** Incorporation of N_d in Eq.2. The low fatality rate scenario has been tested for China. Simulation parameters adjusted on the number of deaths are $q_{c0} = 1.25$, $q_{c\infty} = 0.04$, while $\tau_{ref} = 2$ and $\triangle\tau = 9.0$ and the starting point of the outbreak is set to the 10th of February. The decrease with time of the number of deaths is well reproduced with a $q_{c\infty}$ larger than for he high fatality rate scenario. In this approach, the number of contaminated people is totaly underestimated as shown in Figs. 40 and 41.

- **7-15th of April**: Incorporation of N_d in Eq.2. $q_{c0} = 1.25$, $\tau_{ref} = 2$, $\triangle\tau = 9$ and $q_{c\infty} = 0.04$. Good fit of deaths.

- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

- **17th of April**: jump in the number of deaths (1290) and case (325) at Wuhan that were forgotten.

3.4 South Korea

3.4.1 Initial study

South-Korea was one of the first country except China facing the coronavirus outbreak. Data can be obtained here. It is characterized by two steps as shown in Fig. 46. The first case was identified the 20th of January, and the epidemy was rising exponentialy until the 18th of February, giving up to 31 cases up to that time with a single death. As shown in Fig. 43, the outbreak was rapidly controlled, but the initial growth rate was fairly low and falls down rapidly as shown in Fig. 44. Simulations parameters are $q_{c0} = 0.5$, $q_{c\infty} = 0.01$, with $\tau_{ref} = 4$ and $\triangle\tau = 4.5$, and the end of the outbreak is expected after 40 days (see Fig. 45)

Unfortunately, after a member of the Shincheonji religious organisation was detected as contaminated during a large meeting, the growth rate of the number of contaminated people was

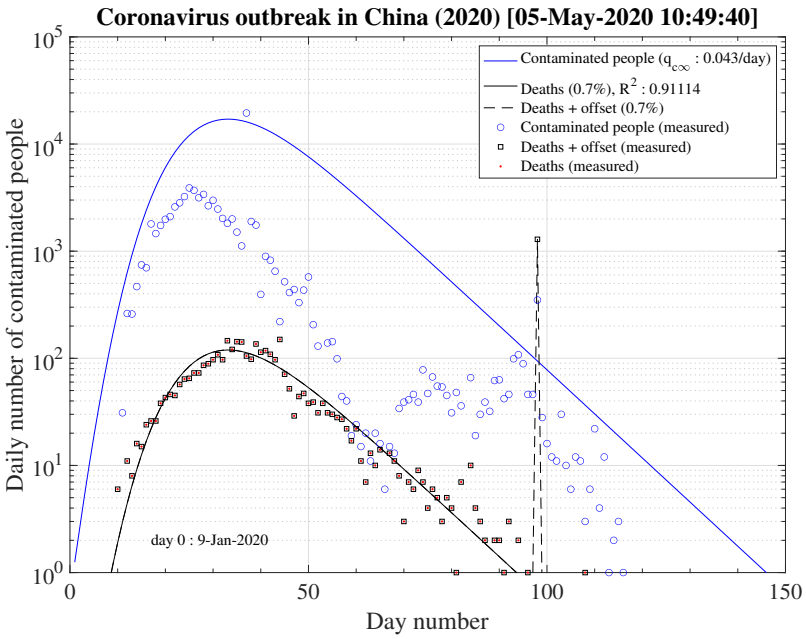

Figure 41: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

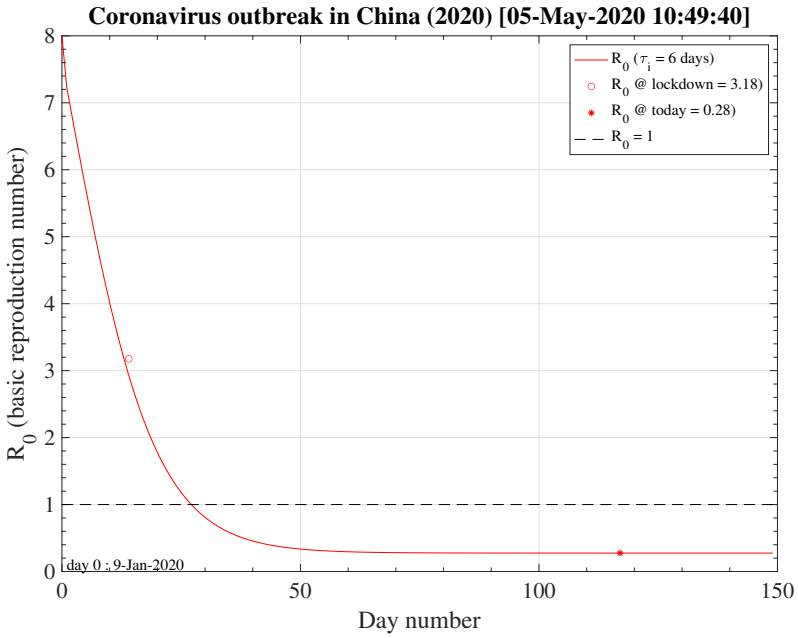

Figure 42: Evolution of the basic reproduction number R_0. Low fatality rate scenario.

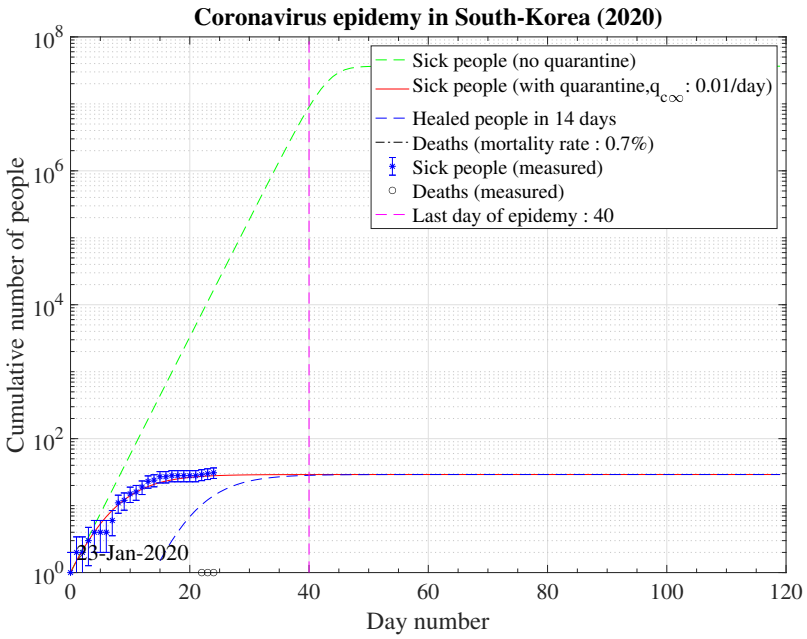

Figure 43: Number of contaminated and dead people by the coronavirus outbreak in South-Korea.

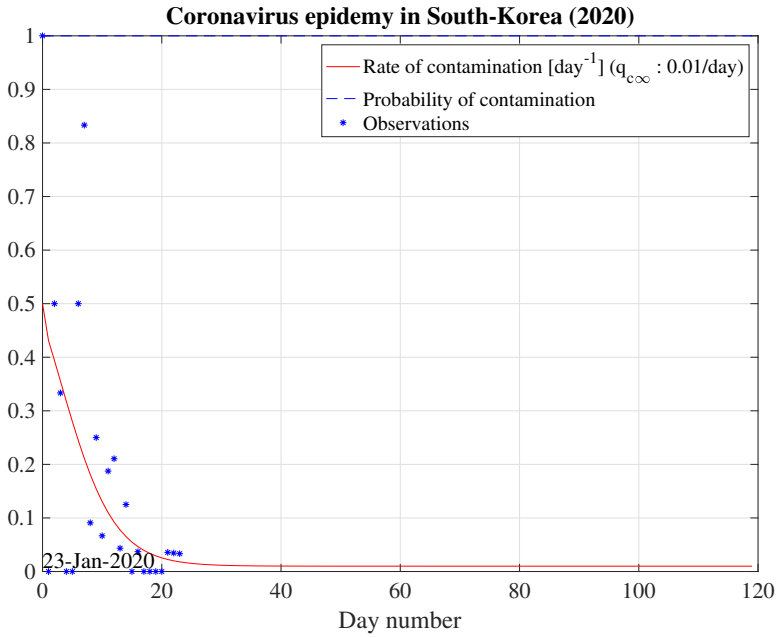

Figure 44: Contamination rate per day and per person and probability of contamination.

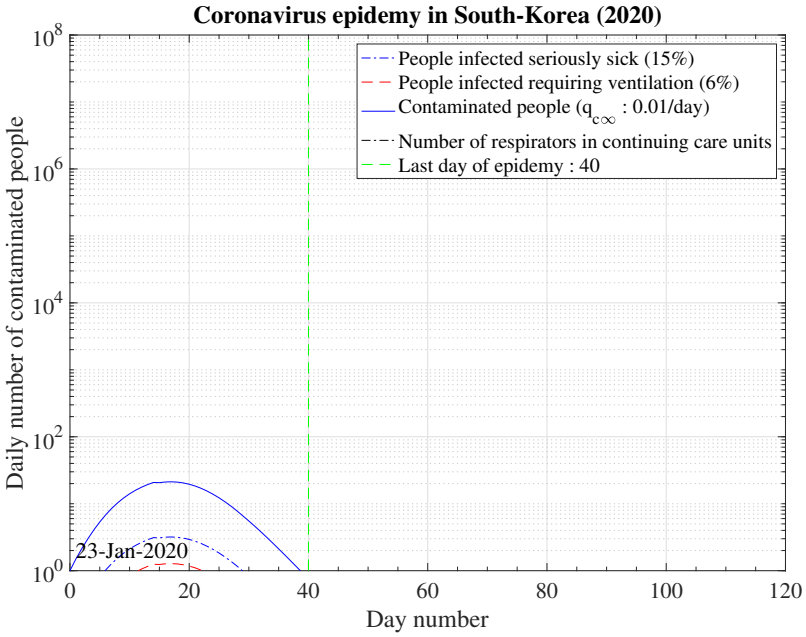

Figure 45: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

suddenly explosive, and the governement reacted immediately by setting up a strong quarantine. This led to a quick decrease of the contamnation rate $q_c\,(t)$ and a fast stabilisation of the outbreak that is back under control with $q_{c\infty} = 0.01$ as shown in Fig. 47. This highlight the importance to cancel all meetings with a large number of participants, and also the fast that since most of the population is not immunited against the virus, the outbreak can restart almost immediately. Therefore, even if the outbreak ends, a continuous control is necessary with fast reaction to avoid an avalanche effect. As shown in Fig. 46 the time evolution of the epidemy is well reproduced, as well as the number of deaths. New simulations parameters after day 24 are $q_{c0} = 1.05$, $q_{c\infty} = 0.01$, with $\tau_{ref} = 4 + 24 = 28$ and $\triangle\tau = 4.5$, indicating that it was a bit more difficult to control the second rise of the outbreak. Nevertheless, Korean authorities were able return back to a controlable situationn, but the outbreak is postponed and last at around 68 days after the initial reference time here considered, the 23th of January, so by end of March (Fig. 48)

Suprinzigly, the fatality rate is much lower, about $\delta_d = 0.7\,\%$, while it may be about $3-4\,\%$ transiently, though statistical uncertainty is very large. Nevertheless, the drop of the mortality may indicate that the quarantine has led to isolate the most fragile population to the virus.

3.4.2 Latest analysis (high fatality rate scenario)

- **11th of March:** the progressive stabilisation of the outbreak is confirmed.
- **12th of March**: the number of deaths starts to become slightly inconsistent with the number of confirmed cases. This is very interesting thanks to the good quality and massive number of diagnostics. This may indicate that the outbreak is not fully stabilized in this country that it is supposed.
- **13th of March**: The parameters are unchanged, and the outbreak seems to be stabilized. The number of deaths is slightly increasing.
- **14th of March**: Unchanged evolution.
- **15th of March**: The number of deaths increases much faster since several days than the number of confirmed cases. This inconsistency is likely the consequence of an under de-

termination of the number of people effectively contaminated. No simulation parameters have been changed.

- **16th of March**: Unchanged evolution.
- **17th of March**: Unchanged evolution.
- **18th of March**: Unchanged general evolution. Number of deaths increased back a bit more than expected. The outbreak is not yet well stopped.
- **19th of March:** confirmation that the outbreak restarts, either on the number of deaths and the number of certified cases. So the outbreak is not on the path to be controlled yet. Perhaps, it is related to the religious group contamination that has not followed the confinement rules. Parameters are not changed yet but will be if this confirmed in next days. (Fig. 45)
- **20th of March:** Same evolution for the number of confirmed cases. Outbreak restarts.
- **21-26th of March:** Same evolution for the number of confirmed cases. Outbreak restarts, but the number of new cases seems stabilised.
- **27-29th of March:** Same evolution for the number of confirmed cases. The number of deaths is rising seriously now, and it is at the highest value of all the outbreak in this country. Something is going wrong.
- **30-31th of March**: No change.
- **1st-3rd of April**: No change.
- **4th of April**: No change for the number of certified cases. The number of deaths decreases.
- **5th of April**: the daily number of certified cases is decreasing by a factor 2.
- **6-17th of April:** Incorporation of N_d in Eq.2. If one consider consistently that only the number of deaths matters, then $q_{c0} = 1.05$, $q_{c\infty} = 0.01$, while $\tau_{ref} = 4+24$ and $\triangle\tau = 4.5$. No optimisation of the simulation parameters, to highlight the flat plateau.

3.5 Iran

3.5.1 Initial study

The coronavirus outbreak is major issue in Iran. From data that can be obtained here. Afster a fast raise of the outbreak, first stabilization after about two weeks. Before, no control of the outbreak was observed, since the data follows the curve without quarantine. The values are quite usual, $q_{c0} = 0.75$, $\triangle\tau = 2.0$, $\tau_{ref} = 2$ and $q_{c\infty} = 0.1$, but $\tau_{ref} = 15$ which means that the authorities reacted late, explaining why the number of confirmed cases is so large. Neverthless, the quarantine-like in Iran was quite effective, since $q_{c\infty} = 0.1$, quite low as compared to European coutries and USA, leading to a stabilization of the growth rate of the number of confirmed caes, but not a control of the outbreak.

In the early phase of the outbreak, the number of deaths was very large, and this is not well explained, except if the initial numbers are wrong, and the outbreak started well before as it was claimed (like in South Korea, with a two steps evolution). At the date of the 11th of March, the fatality rate reaches $\delta_d = 3.0\,\%$, consistently with other countries. The small rise observed after the 9th of March may result from a restart of the outbreak, that is not correctly followed by the counting of the confirmed cases.

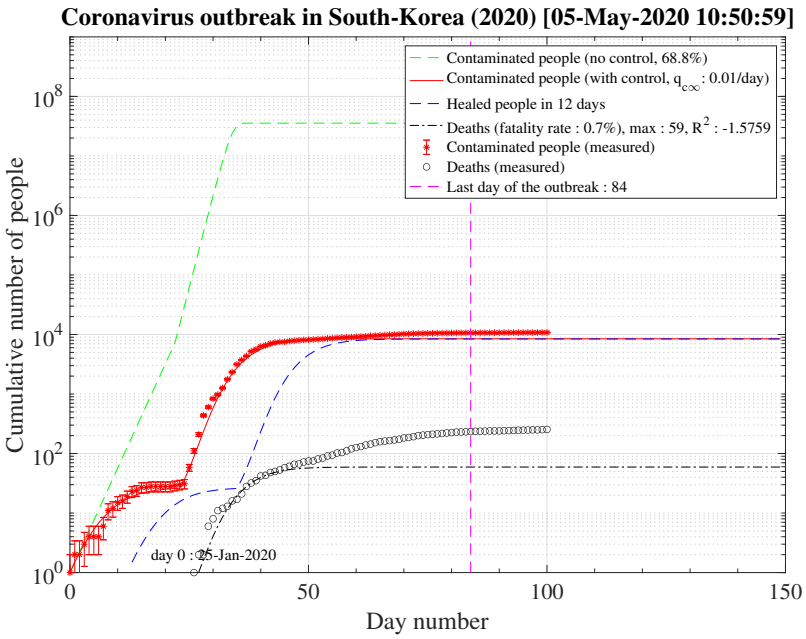

Figure 46: Number of contaminated and dead people by the coronavirus outbreak in South-Korea.

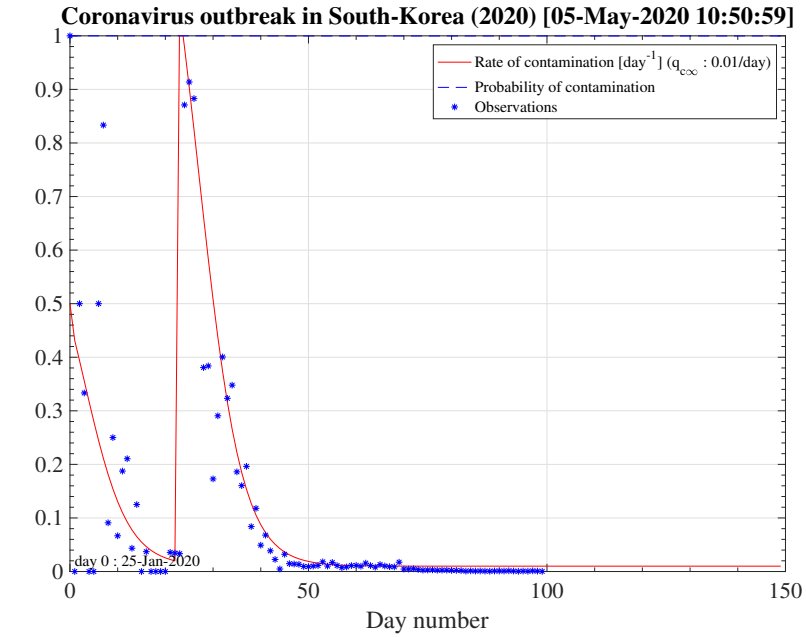

Figure 47: Contamination rate per day and per person and probability of contamination.

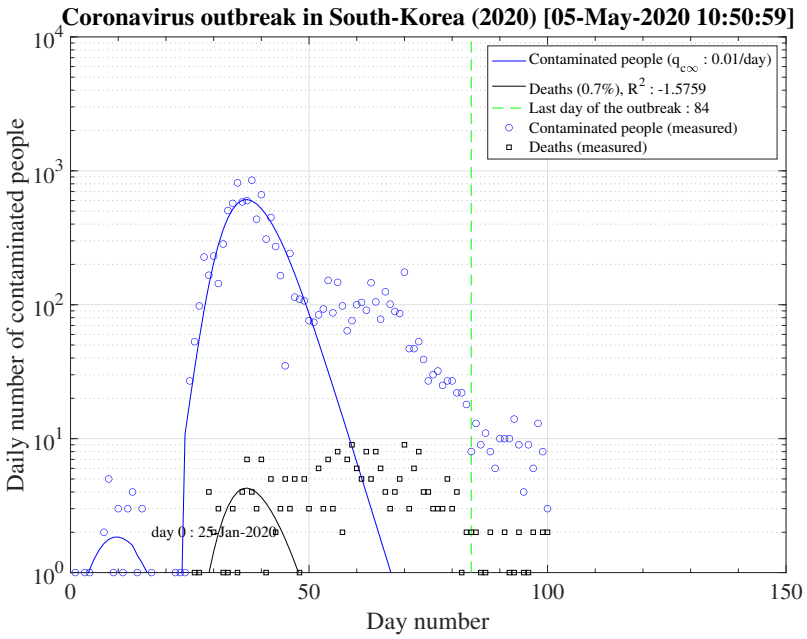

Figure 48: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

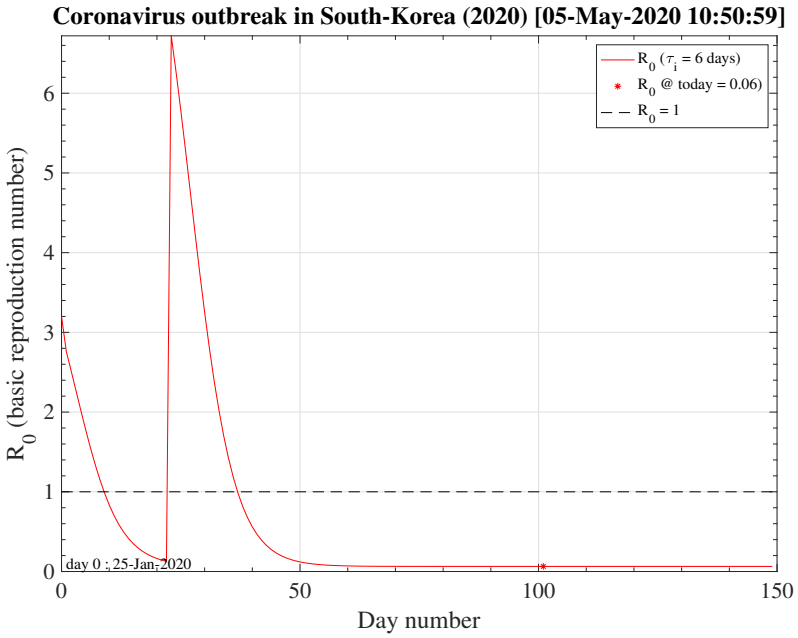

Figure 49: Evolution of the basic reproduction number R_0. High fatality rate scenario.

3.5.2 Latest analysis (high fatality rate scenario)

- **12th of March**: the number of deaths become again inconsistent with the number of confirmed cases from the last three days. Likely the latter is underestimated.
- **13th of March**: same evolution than previous day.
- **14th of March**: Unchanged evolution.
- **15th of March**: The residual rate $q_{c\infty}$ is lowered back to 0.1 to fit the observed number of confirmed cases. Nevertheless, the number of deaths increases much faster since several days. This inconsistency is likely the consequence of an under determination of the number of people effectively contaminated. The low fatality rate scenario is likely more appropriate in this case. It may be also the consequence of a saturation of the health care system, with a marked excess mortality.
- **16th of March**: nothing changed since previous days.
- **17th of March**: nothing changed since previous days.
- **18th of March**: nothing changed since previous days. Trends remain the same like inthe 15th of March.
- **19-21th of March**: nothing changed since previous days.
- **22-23th of March**: A change of slope of te number of deaths is visible since day 21. To have a better fit of the data since about ten days, simulation parameters are $q_{c0} = 0.22$, $\triangle\tau = 10.0$, $\tau_{ref} = 10 + 21$ and $q_{c\infty} = 0.05$ since this reference day. If this is confirmed, the number of days to reach the outbreak peak from the beginning of the outbreak is 46 (06-Apr-2020). The duration of the outbreak is larger than 120 days (19-Jun-2020), and th total number of deaths estimated to 10511. Regarding the health care situation in Iran, these numbers are subject to change significantly.
- **24-26th of March**: The outbreak reaches its peak, within large uncertainty. The decrease of the outbreak is difficult to predict, but seems slow. So the outbreak shoudl stop after end of June, with 3509 deaths. For better timing, $\triangle\tau = 4.0$.
- **27-29th of March**: The peak is likely effectively reached. But, the post peak phase is long: slow decrease of the daily number of deaths. The outbreak is not controled yet, just stabilized.
- **30-31th of March**: No change, the daily number of deaths is globaly decreasing. The rate is slow and data are noisy.
- **1st of April**: the peak is reached but very broad. The further evolution is not clear.
- **2nd-3rd of April**: the peak is likely reached but very broad. There some counting problem in the daily number of deaths, leading to jumps. Only the smooth trend is meaningful. The daily number of certified cases and deaths are back again almost consistent.
- **4-5th of April**: bad day or restart of the outbreak, a real question ! Difficult to say more today.
- **6th of April:** Incorporation of N_d in Eq.2. If one consider consistently that only the number of deaths matters, then $q_{c0} = 0.26$, $q_{c\infty} = 0.05$, while $\tau_{ref} = 10 + 21$ and $\triangle\tau = 4$. Several jump in the daily numbers of deaths, that suggest problem of counting. The trend is a general decrease of the number of deaths with time.
- **7-15th of April**: Single set of parameters : $q_{c0} = 0.93$, $q_{c\infty} = 0.05$, $\tau_{ref} = 4$ days, $\triangle\tau = 10$ days. Better fit over the whole range, except the very beginning. But numbers are rather suspects. The trend is however preserved.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

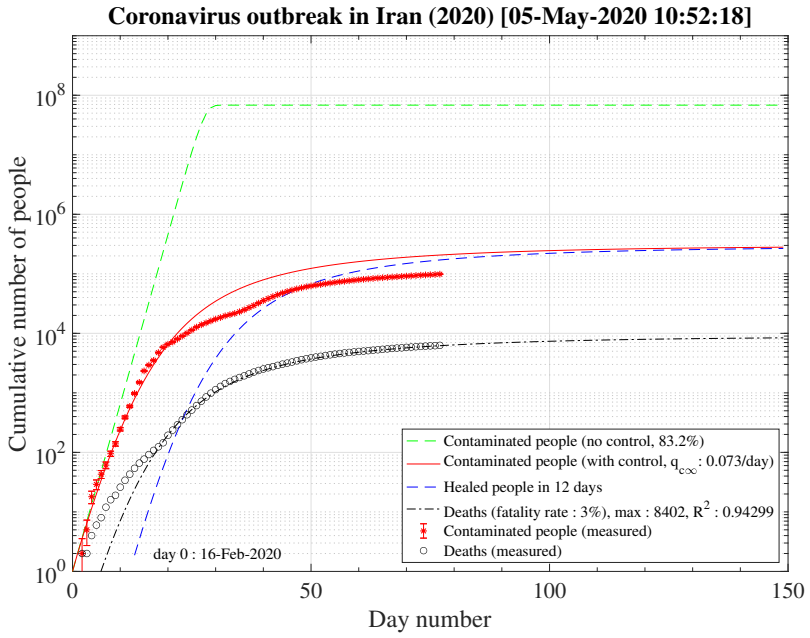

Figure 50: Number of contaminated and dead people by the coronavirus outbreak in Iran. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

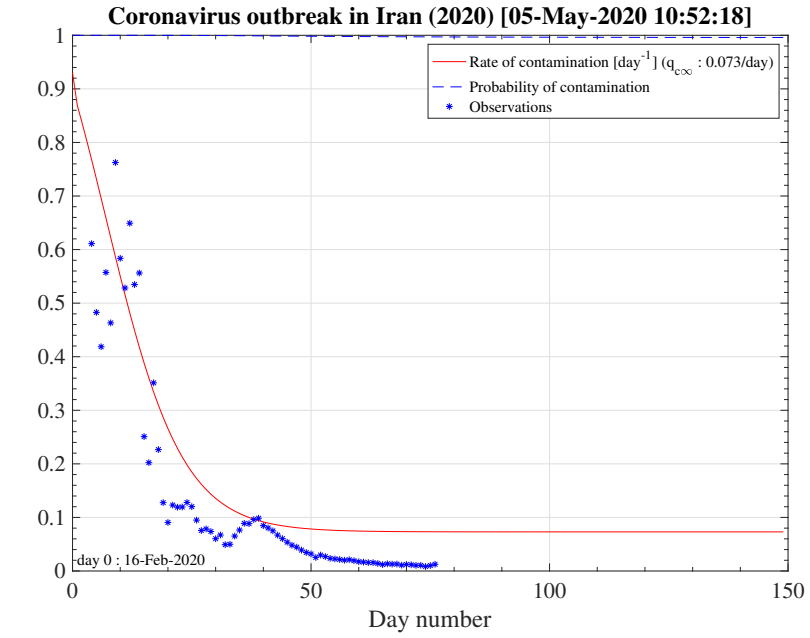

Figure 51: Contamination rate per day and per person and probability of contamination. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

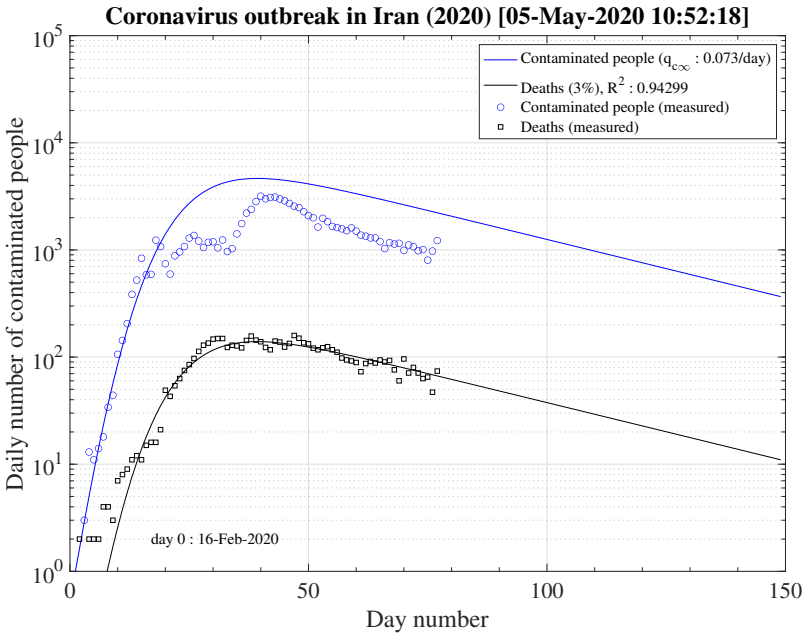

Figure 52: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

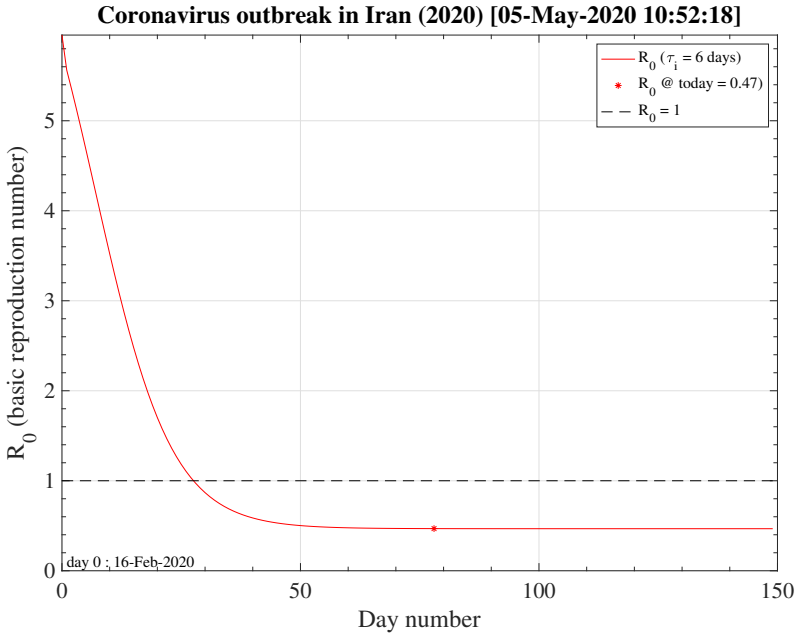

Figure 53: Evolution of the basic reproduction number R_0. High fatality rate scenario.

3.6 Switzerland

3.6.1 Initial study

In Switzerland, the outbreak starts to grow quickly too with $q_{c0} = 0.75$. Status of the outbreak may be found here. The simulation parameters are $\tau_{ref} = 10$ and $\triangle\tau = 2.0$, with $q_{c\infty} = 0.15$, which leads to a rapid growth rate of the number of cases. Nevertheless, the outbreak in not controlled at the date of the 6th of March 2020. The mortality rate is estimated to $\delta_d = 0.4\,\%$, much lower than for France, by a factor 4 at least, since just one death is officaly reported the 9th of February, and two for the 11th of March. Results are shown in Figs. 54, 55 and 56. Regarding the time evolution of the number of confirmed cases, there is large uncertainty on $q_{c\infty}$.

3.6.2 Latest analysis (standard model)

- **12th of March** : fast rise of the number of confirmed cases and deaths. Normalized to the whole population, it is one of the most affected countries. Perhaps a consequence of the proximity with North Italy. The EPFL has closed because of several confirmed cases. The residual contamination rate should be slightly increased to $q_{c\infty} = 0.18$, but the fatality rate is now set to $\delta_d = 4\,\%$, like in other coutries to have at least the level, not yet the time dependence, because the absolute level is too low. Another interpretation is that the fast rise of the nuber of deaths is a sign that the number of cases is strongly underestimated. If this is exact, $q_{c\infty} = 0.3$,$\delta_d = 0.4\,\%$ is unchanged and the number of contaminated people is underestimated by a factor two approximately. Coming days will be very interesting to decide between the two approaches.
- **13th of March:** $q_{c\infty} = 0.2$ and $\delta_d = 0.7\,\%$ gives better global results with observations on the whole dataset. The number of deaths start to rise significantly and reach standard values observed in other countries, while it was very much lower before. Likely statistical uncertainty. With $q_{c\infty} = 0.2$, the outbreak is not under control.
- **14th of March**: Unchanged evolution.
- **15th of March**: The trend is similar as previous days. The number of confirmed cases seems to jump faster. To be confirmed.
- **16th of March**: no data.
- **17-18th of March**: Unchanged evolution.
- **19th of March**: Unchanged evolution. Perhaps a small accelaration of the outbreak to be confirmed.
- **20th of March:** no data.
- **21-26th of March:** Unchanged evolution. No control of the outbreak in view.
- **28th of March**: Anomalous jump of the number of deaths.
- **29th of March**: Source of data has been changed, because those from WHO are not accurate. It is take directly from the Git database give in the introduction. New simulation parameters are $q_{c0} = 0.75$, $\tau_{ref} = 10$ and $\triangle\tau = 2.0$, with $q_{c\infty} = 0.2$ have been marginaly modified. No jump in the number of deaths finally. No contro of the outbreak.
- **30th of March-2nd of April**: unchanged evolution.
- **3rd of April** : first signs of a slowing-fown of the number of deaths. The number of people in intensive health care seems to be stable, but very noisy. $q_{c\infty} = 0.19$
- **4th of April** : unchanged trend though slight evolution.
- **5th of April :** more clear evolution of a stabilisation. New simulation parameters are $q_{c0} = 0.55$, $\tau_{ref} = 4$ and $\triangle\tau = 14.0$, with $q_{c\infty} = 0.1$ for a better fit all over the time. The peak of the outbreak is estimated the 29th of May.

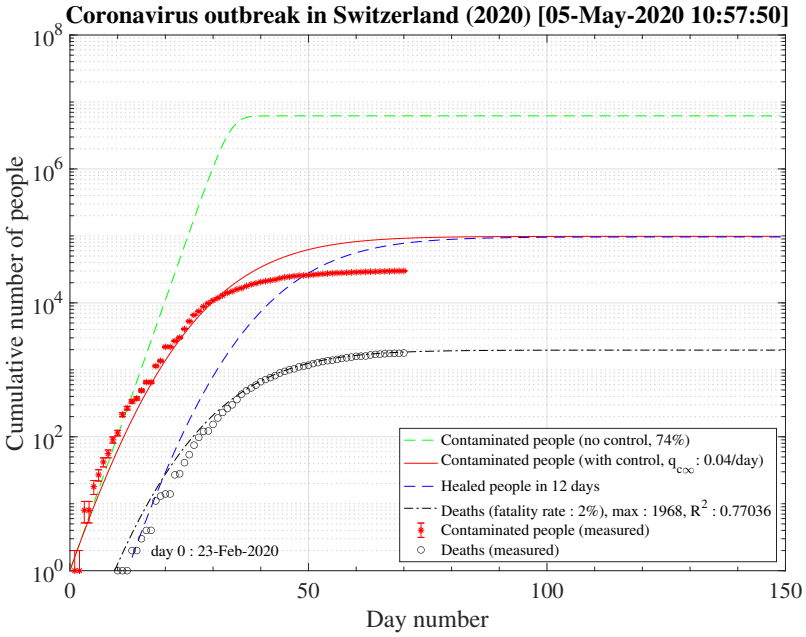

Figure 54: Number of contaminated and dead people by the coronavirus outbreak in Switzerland. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

- **6th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.57$, $q_{c\infty} = 0.1$, while $\tau_{ref} = 4$ and $\triangle\tau = 14$.
- **7-8th of April**: Single set of parameters : $q_{c0} = 0.57$, $q_{c\infty} = 0.1$, $\tau_{ref} = 4$ days, $\triangle\tau = 14$ days. Better fit over the whole range.
- **9-13th of April**: Single set of parameters : $q_{c0} = 0.6$, $q_{c\infty} = 0.05$, $\tau_{ref} = 4$ days, $\triangle\tau = 15$ days. Better fit over the whole range, and sign of stabiliation better described.
- **14-15th of April**: Optimized simulation parameters : $q_{c\infty} = 0.049$
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

3.7 United States of America

3.7.1 Initial study

The outbreak starts to be quite aggressive in United-States of America. Several states have declared the emergency state. Nevertheless, the domestic outbreak by local spread of the virus seems to have started at the date of 19th of Febrary, as indicated by the two steps evolution of the number of the confirmed cases in Fig. 59. For the second rise, simulation parameters are $q_{c0} = 0.4$, with $\tau_{ref} = 7$ and $\triangle\tau = 2.0$. It is a rather slow growth rate, perhaps because the country was already prepared to face the outbreak. Nevertheless, with $q_{c\infty} = 0.4$, the outbreak is not controlled. Note that $q_{c0} = 0.4$ is rather low as compared to other countries, and this may result from the fact that the population density is lower in USA than in other countries, so the probability to contaminate somebody is lower.

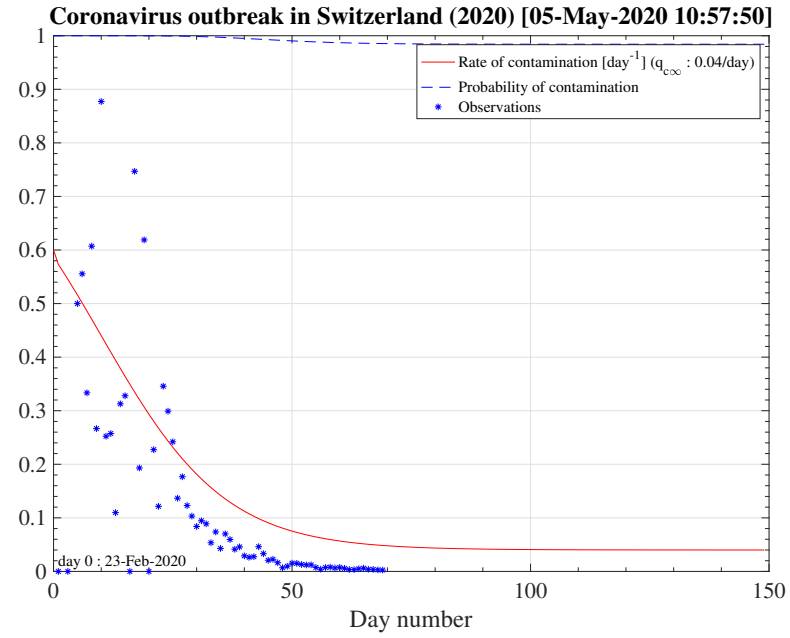

Figure 55: Contamination rate per day and per person and probability of contamination. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

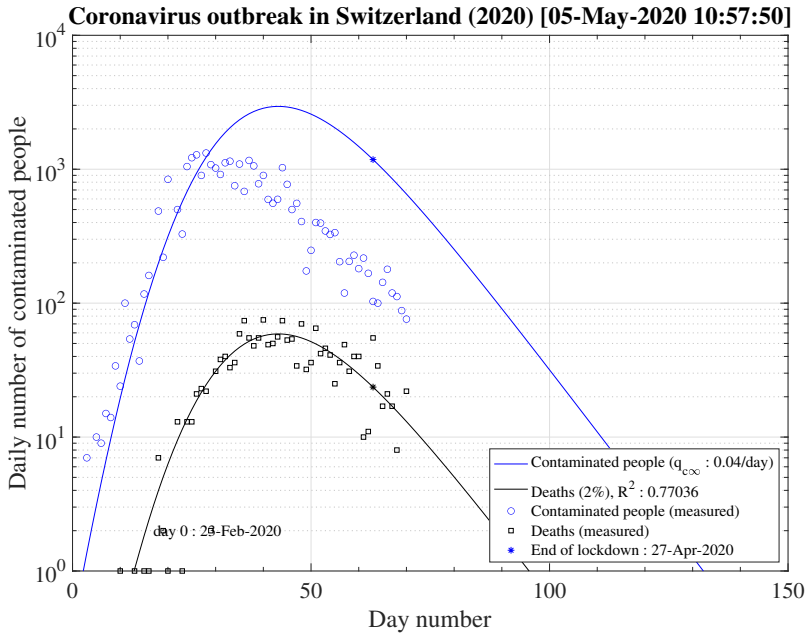

Figure 56: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

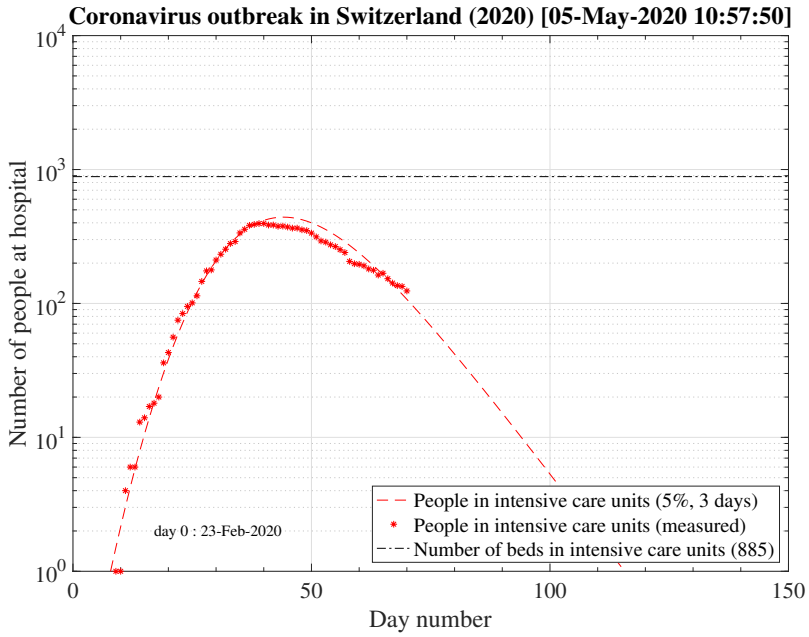

Figure 57: Number of people in intensive care units, fraction of the contaminated people, and additional delay, thanks to recovery time. High fatality rate scenario.

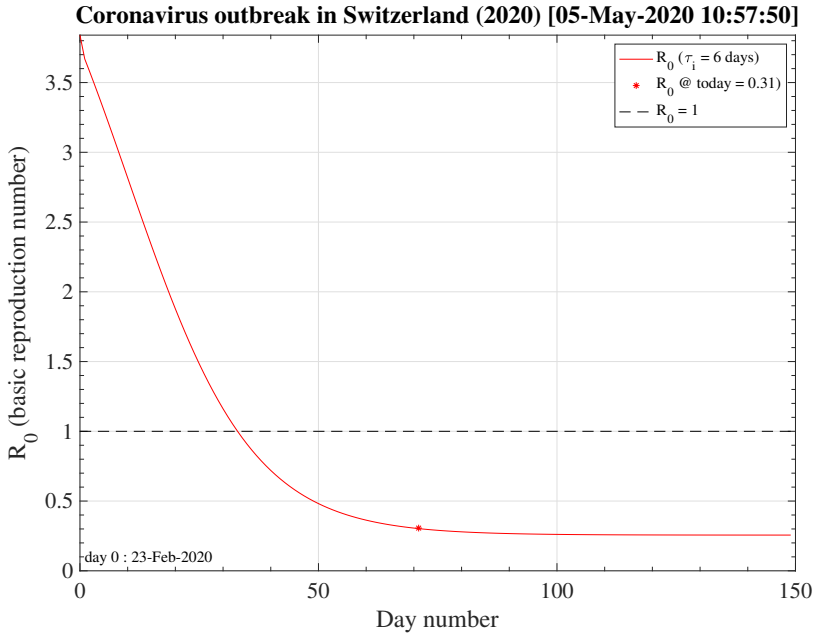

Figure 58: Evolution of the basic reproduction number R_0. High fatality rate scenario.

3.7.2 Latest analysis (high fatality rate scenario)

- **12th of March**: the evolution is consistent with initial parameters of the model.
- **13th of March:** Slow change in the dynamics of the outbreak. The resiudal contamination rate must be lowered down to $q_{c\infty} = 0.26$. The number of deathsis rising, but more slowly. The fatality rate shoudl be lowered down to $\delta_d = 3.0\,\%$ closer to more standard values. Nevertheless, more points are necessary to be more precise.
- **14th of March**: Unchanged evolution.
- **15th of March**: Unchanged evolution.
- **16th of March**: Unchanged evolution.
- **17th of March**: Slight acceleration of the outbreak: $q_{c\infty} = 0.29$. For a better agreement of the number of deaths, $\delta_d = 2.0\,\%$.
- **19-26th of March**: Unchanged evolution.
- **27-28th of March**: A noticeable jump of the number of contaminated people and deaths. Acceleration of the outbreak or counting problem ?
- **29-30th of March**: Unchanged evolution. No acceleration of the outbreak.
- **1st-3rd of April**: Unchanged evolution. No acceleration of the outbreak.
- **4th of April**: slight slowing-down observed. Simulation parameters have been optimized. $q_{c0} = 0.4$, with $\tau_{ref} = 7$ and $\triangle\tau = 12.0$ and $q_{c\infty} = 0.23$.
- **5th of April** : continuation of a slight slowing-down. Parameters not yet changed.
- **6th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.41$, $q_{c\infty} = 0.23$, while $\tau_{ref} = 24 + 17$ and $\triangle\tau = 13$.
- **7th of April**: Single set of parameters : $q_{c0} = 0.39$, $q_{c\infty} = 0.01$, $\tau_{ref} = 17 + 31$ days, $\triangle\tau = 16$ days. Better fit over the whole range.
- **8th of April**: Parameters slightly modified $q_{c0} = 0.385$, $\tau_{ref} = 17 + 32$ days, but general trend unchanged.
- **9-10th of April**: Parameters modified $\tau_{ref} = 17 + 33$ days, and $\triangle\tau = 7$. but general trend unchanged.
- **11-13th of April**: Slight increase $q_{c\infty} = 0.015$.
- **14-15th of April**: complicated situation. The outbreak seems to restart.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

3.8 Spain

3.8.1 Initial study

The case of Spain is very similar to USA.The outbreak started effectively the 23th of February, and the evolution is well modeled by following parameters: $q_{c0} = 1.0$, $q_{c\infty} = 0.25$, with $\tau_{ref} = 7$ and $\triangle\tau = 2.0$. There is no specificity of Spain as compared to other countries. The initial phase of the outbreak seems to have been slightly more agressive, but the contimation rates felt down rapidly to standard European levels, ranging between $q_{c\infty} = 0.20 - 0.30$. Obviously, the outbreak is not under control at this stage. All results can been seen in Figs. 63, 64 and 65.

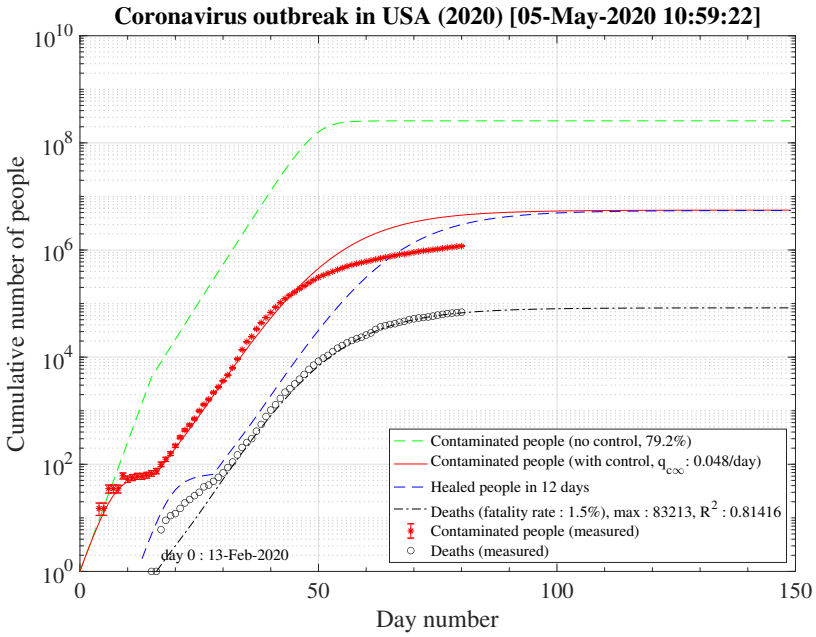

Figure 59: Number of contaminated and dead people by the coronavirus outbreak in United States of America. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

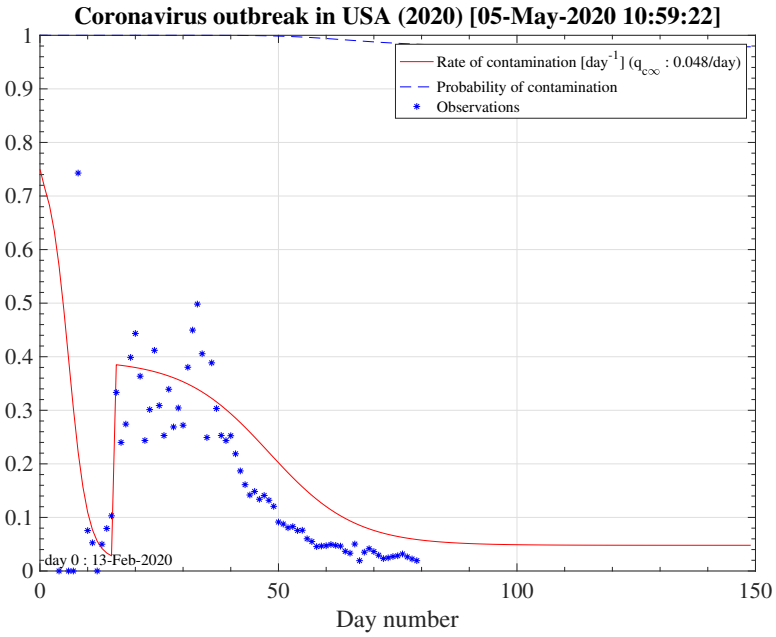

Figure 60: Contamination rate per day and per person and probability of contamination. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

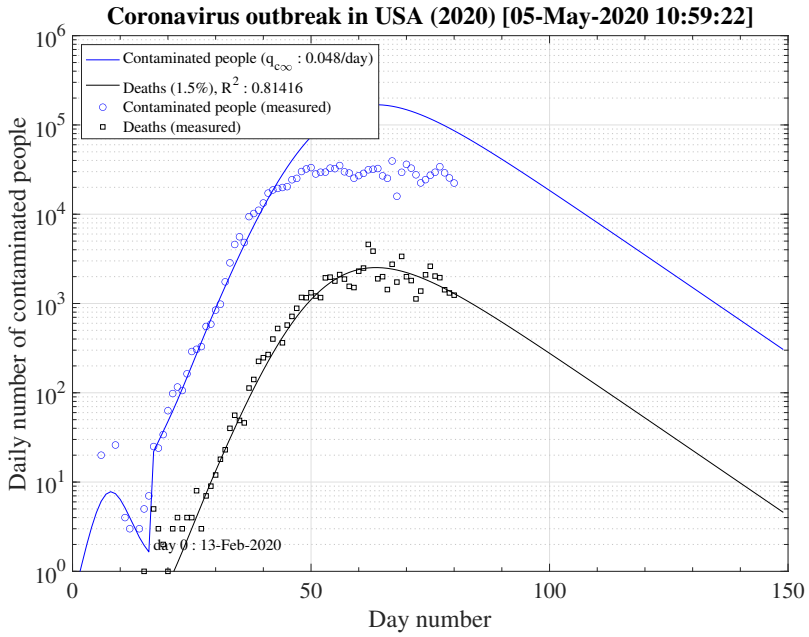

Figure 61: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

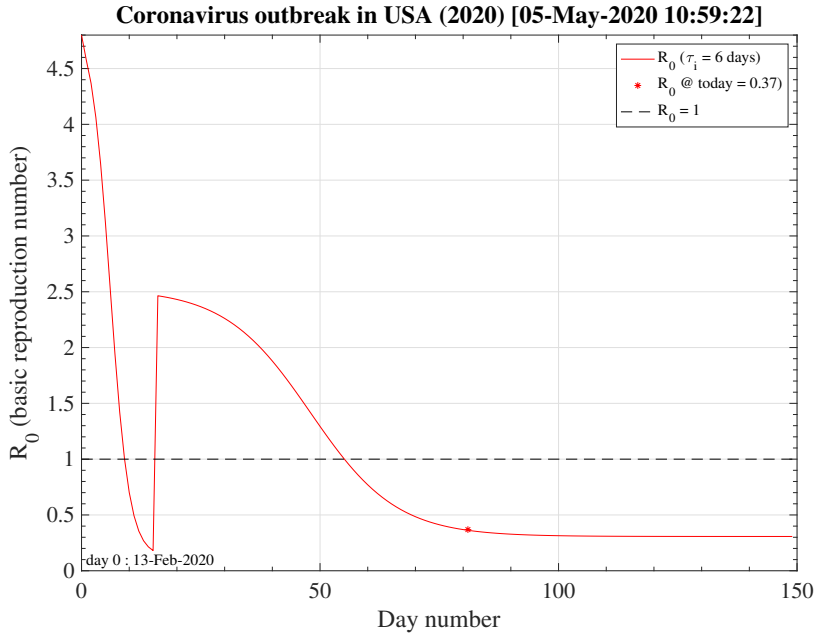

Figure 62: Evolution of the basic reproduction number R_0. High fatality rate scenario.

3.8.2 Latest analysis (high fatality rate scenario)

- **12th of March**: the evolution is consistent with initial parameters of the model.
- **13th of March**: the evolution is still consistent with initial parameters of the model. The country becomes the second with largest number of confirmed cases, ahead from France.
- **15th of March**: Unchanged evolution. People are afraid by the numbers, but this is the standard exponential growth.
- **16th of March**: Unchanged evolution.
- **17th of March**: Unchanged evolution.
- **18th of March**: Unchanged evolution.
- **19-20th of March**: Unchanged evolution. Exponential growth is unchanged, slightly above the expected value.
- **21-23th of March**: Unchanged trend. The residual contamination rate must be increased to $q_{c\infty} = 0.34$. The discrepancy between the deaths and cases growth rates is typical of a situation where the number of tests gives only a rough estimate of the actual number of contaminated persons.
- **24th of March:** perhaps a very small evolution. The coming days may give indications.
- **25th of March:** first small signs that the peak of outbreak is coming. Simulation parameters from the day of the confinement (day 23, 15th of March) are : $q_{c0} = 0.34$, $q_{c\infty} = 0.04$, with $\tau_{ref} = 29$ and $\triangle\tau = 10.0$. The date of the expected peak is around 10th of April with a very large uncertainty.
- **26th of March:** update of the values, and no peak in view. Bac to previous parameters until clear signs
- **27th of March:** very bad evolution. No peak in view despite the confinement.
- **28-29th of March:** first signs of the peak coming. Simulation parameters from the day of the confinement (day 23, 15th of March) are : $q_{c0} = 0.34$, $q_{c\infty} = 0.18$, with $\tau_{ref} = 6+23$ and $\triangle\tau = 4.0$. The peak is expected the the 3rd of May 2020, but will occur earlier likely.
- **30th of March**: the soon occurence of the outbreak peak is confirmed, but still far.
- **1st-2nd of April**: Finally, the situation has likely changed completely, and the outbreak peak is likely past. Sharp peak without clear precursor. Simulation parameters have been deeply changed, and are $q_{c0} = 0.34$, $q_{c\infty} = 0.06$, with $\tau_{ref} = 11 + 23$ and $\triangle\tau = 2.0$. The strong confinement imposed to the population may be the reason of the sharp peak. Further days will give more details on the trend.
- **3rd of April**: the peak is certainly reached, but it may be larger than initially expected. $q_{c\infty} = 0.08$.
- **4th of April :** the peak is broad. Unchanged simulation parameters.
- **5th of April :** In order to have a better fit of the peak, simulation parameters are $q_{c0} = 0.36$, $q_{c\infty} = 0.01$, with $\tau_{ref} = 11 + 23$ and $\triangle\tau = 5.0$. The peak was reached the 1st of April, and the end of the outbreak is scheduled for the 18th of May with 16365 deaths.
- **6-9th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.37$, $q_{c\infty} = 0.03$, while $\tau_{ref} = 23 + 11$ and $\triangle\tau = 5$.
- **10-15th of April:** Single set of parameters : $q_{c0} = 0.6$, $q_{c\infty} = 0.045$, $\tau_{ref} = 27$ days, $\triangle\tau = 6$ days. Better fit over the whole range, and sign of stabiliation better described.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

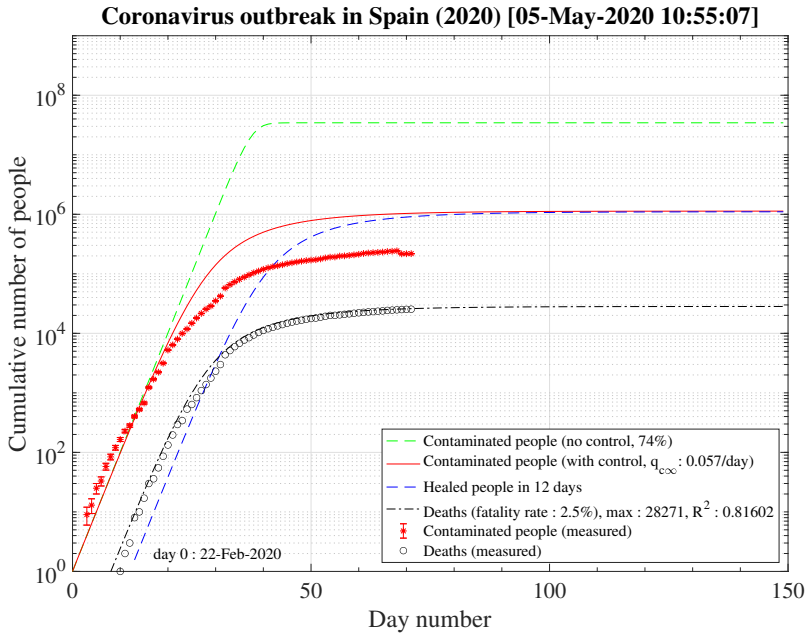

Figure 63: Number of contaminated and dead people by the coronavirus outbreak in Spain. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

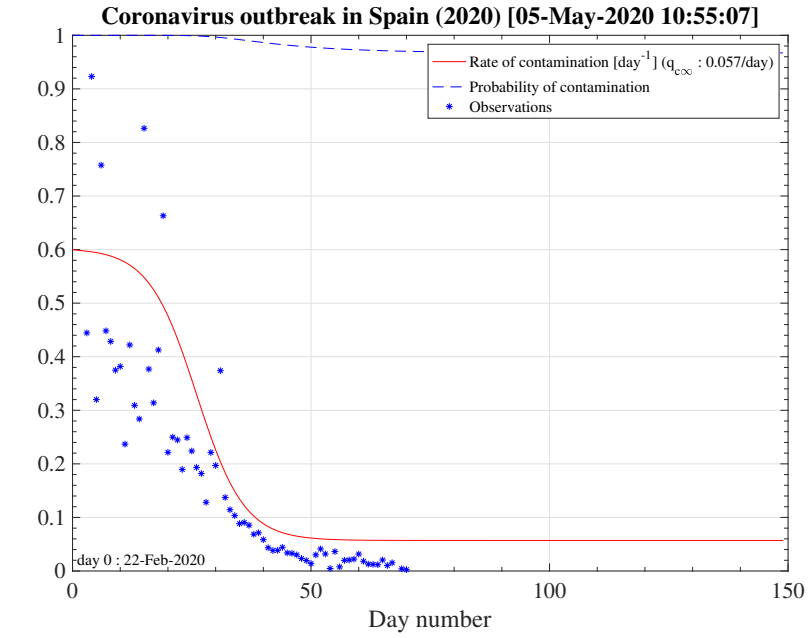

Figure 64: Contamination rate per day and per person and probability of contamination. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

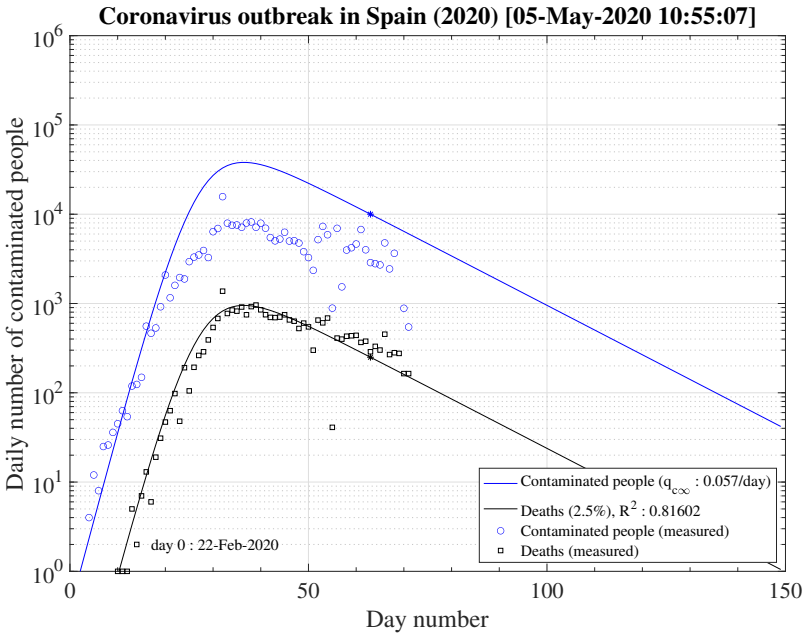

Figure 65: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. High fatality rate scenario. After the 16th of March, the rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

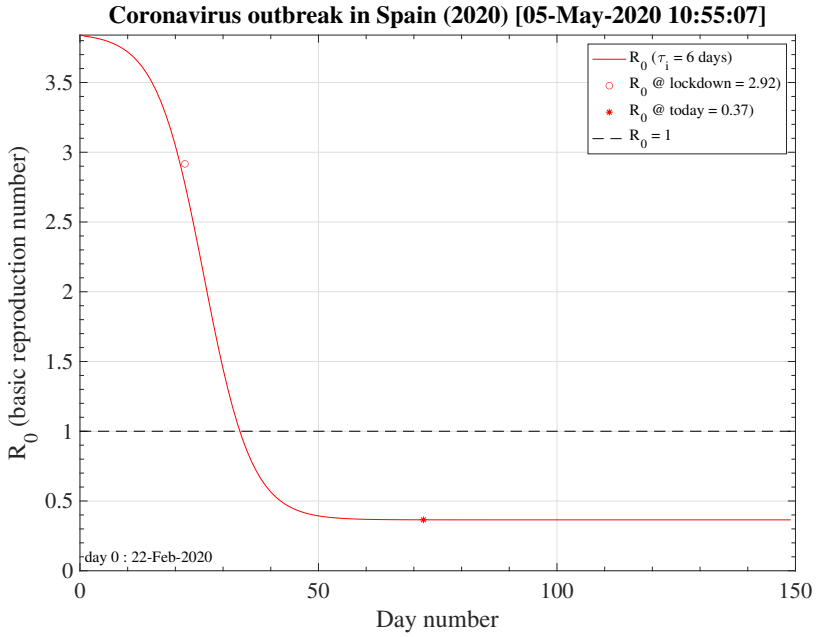

Figure 66: Evolution of the basic reproduction number R_0. High fatality rate scenario.

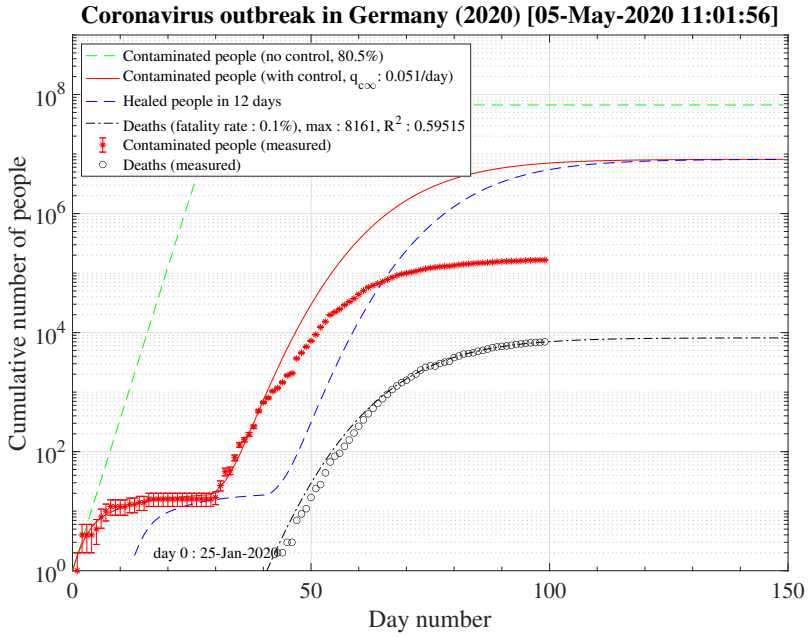

Figure 67: Number of contaminated and dead people by the coronavirus outbreak in Germany.

3.9 Other countries

3.9.1 Germany

- **24-28th of March**: two steps outbreak like South-Korea, Germany or USA. A fast rise of the outbreak is observed. Simulation parameters are $q_{c0} = 0.8$, $q_{c\infty} = 0.14$, with $\tau_{ref} = 32$ and $\triangle\tau = 8.0$. The fatality rate is very low $\delta_d = 0.3\,\%$ since the number of people which died from the coronavirus seems to be underestimated. Therefore, the parameters are adjusted to fit the certified number of contaminated people. All results can been seen in Figs. 676869.

- **29-31th of March:** no change. Same evolution.

- **1st-2nd of April:** no change. Same evolution.

- **3rd-4th of April:** Slight slowing-down. New simulations parameters are $q_{c0} = 0.75$, $q_{c\infty} = 0.20$, with $\tau_{ref} = 32$ and $\triangle\tau = 10.0$.

- **5th of April** : continuation of a slight slowing-down. New simulations parameters are $q_{c0} = 0.73$, $q_{c\infty} = 0.06$, with $\tau_{ref} = 32$ and $\triangle\tau = 16.0$.

- **6-8th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.73$, $q_{c\infty} = 0.06$, while $\tau_{ref} = 30 + 1$ and $\triangle\tau = 16$.

- **9-10th of April:** $\tau_{ref} = 30 + 2$. All other parameters unchanged, for a better fit of latest days evolution.

- **11-15th of April:** Slight decrease, $q_{c\infty} = 0.05$.

- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

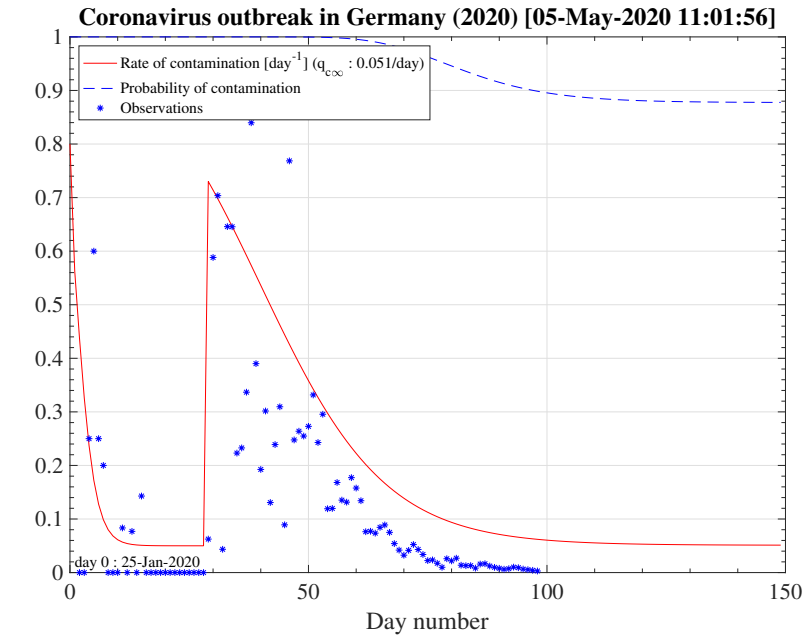

Figure 68: Contamination rate per day and per person and probability of contamination.

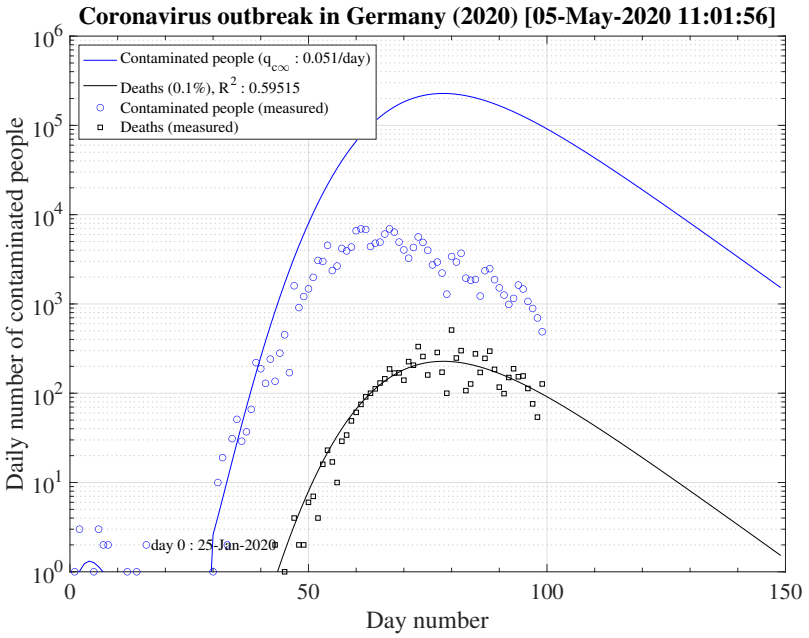

Figure 69: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

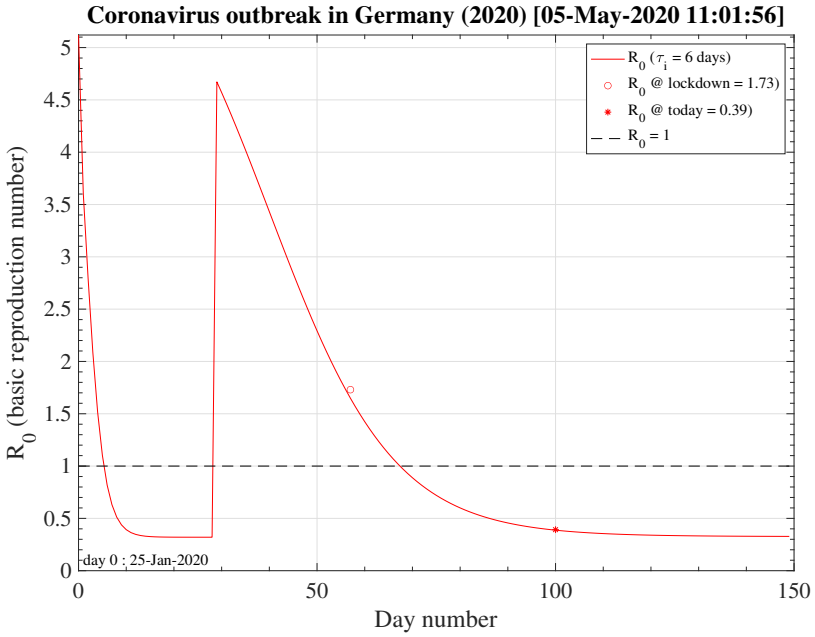

Figure 70: Evolution of the basic reproduction number R_0. High fatality rate scenario.

3.9.2 United-Kingdom

- **24-25th of March**: two steps outbreak like South-Korea or USA and Germany. A fast rise of the outbreak is observed. Simulation parameters (high fatality rate scenario) are $q_{c0} = 1.4$, $q_{c\infty} = 0.33$, with $\tau_{ref} = 26$ and $\triangle\tau = 2.0$. The fatality rate is rather low $\delta_d = 1.0\,\%$. All results can been seen in Figs. 717273
- **26-28th of March**: Strange evolution of the number of deaths... To be followed.
- **29-31th of March:** The evolution is as expected from the model. So regular exponential growth.
- **1st-5th of April:** The evolution is as expected from the model. So regular exponential growth.
- **6th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.9$, $q_{c\infty} = 0.28$, while $\tau_{ref} = 24 + 2$ and $\triangle\tau = 6$.
- **7-8th of April**: Single set of parameters : $q_{c0} = 0.51$, $q_{c\infty} = 0.02$, $\tau_{ref} = 22 + 33$ days, $\triangle\tau = 10$ days. Better fit over the whole range.
- **9-15th of April**: $q_{c\infty} = 0.03$ and $\triangle\tau = 11$ for a better fit.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

3.9.3 Québec (canada)

- **24-25th of March**: A moderate rise of the outbreak is observed. Simulation parameters (high fatality rate scenario) are $q_{c0} = 0.5$, $q_{c\infty} = 0.3$, with $\tau_{ref} = 2$ and $\triangle\tau = 4.0$. Surprizingly, the fatality rate is high $\delta_d = 4.0\,\%$, like China and USA. All results can been seen in Figs. 757677

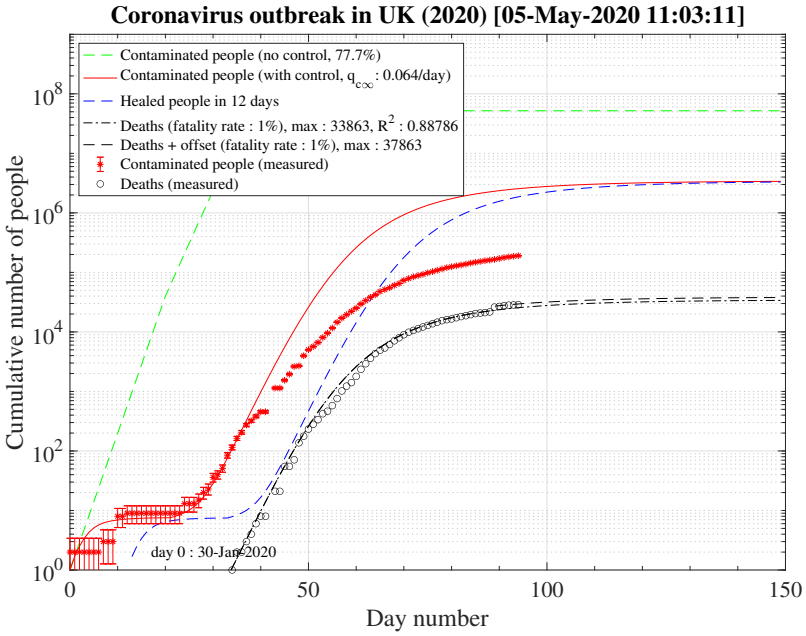

Figure 71: Number of contaminated and dead people by the coronavirus outbreak in United-Kingdom. High fatality rate scenario. The rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

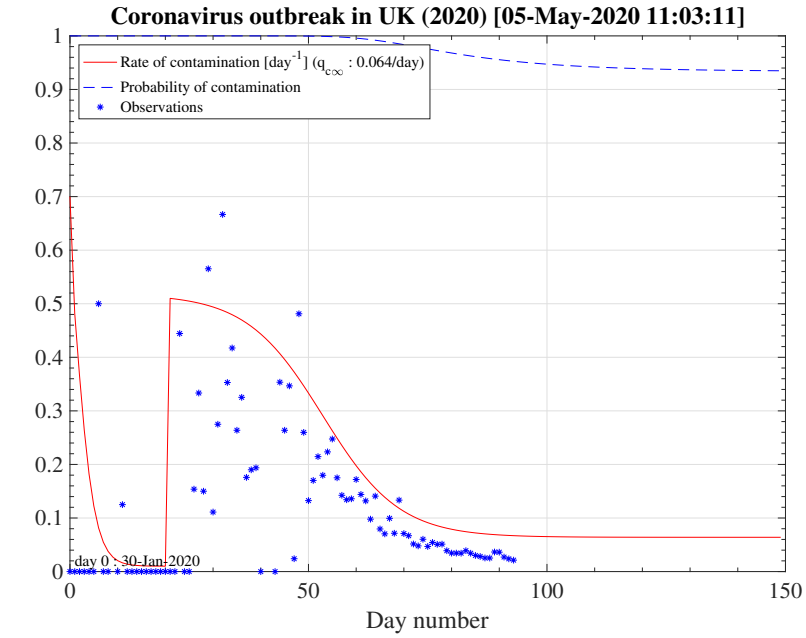

Figure 72: Contamination rate per day and per person and probability of contamination. High fatality rate scenario. The rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

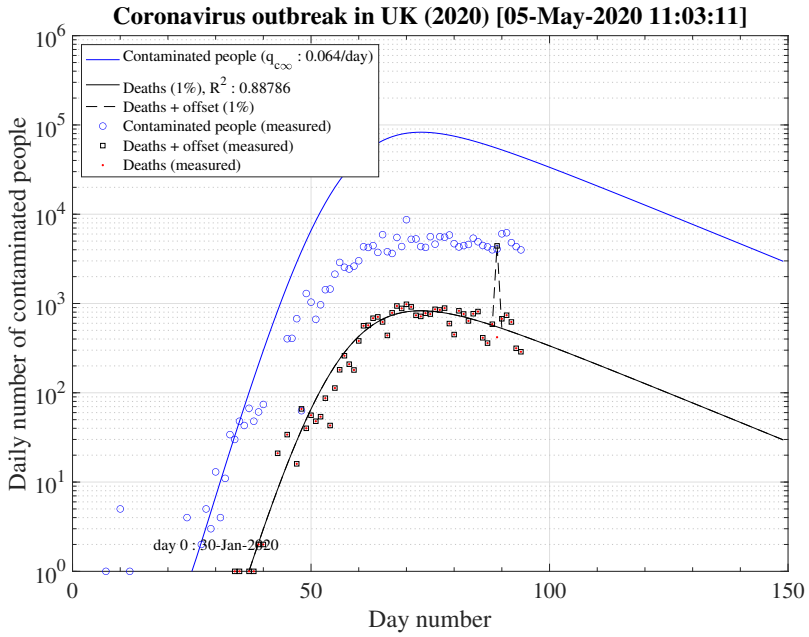

Figure 73: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation. High fatality rate scenario. The rate of contamination is adjusted to fit the number of deaths (daily and cumulative) and not the number of contaminated people. See explanations in the main text.

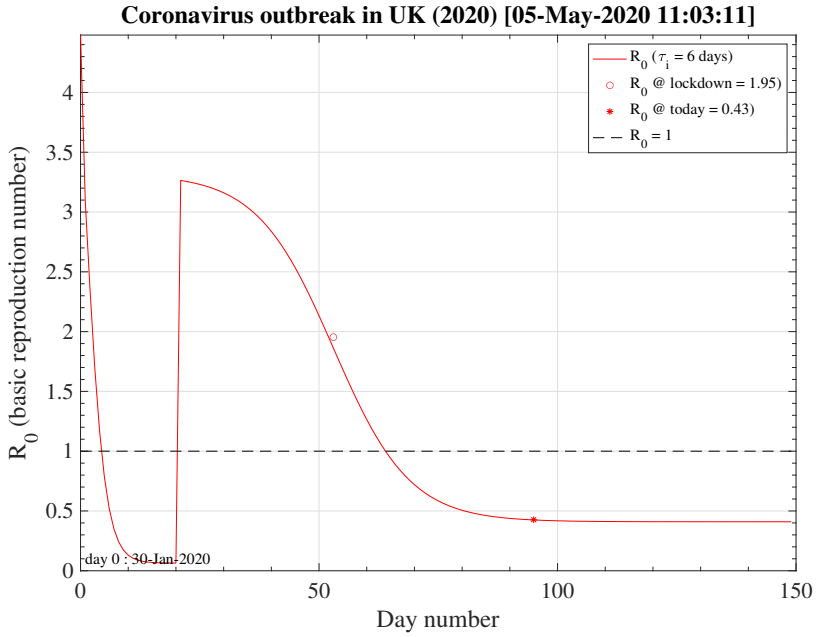

Figure 74: Evolution of the basic reproduction number R_0. High fatality rate scenario.

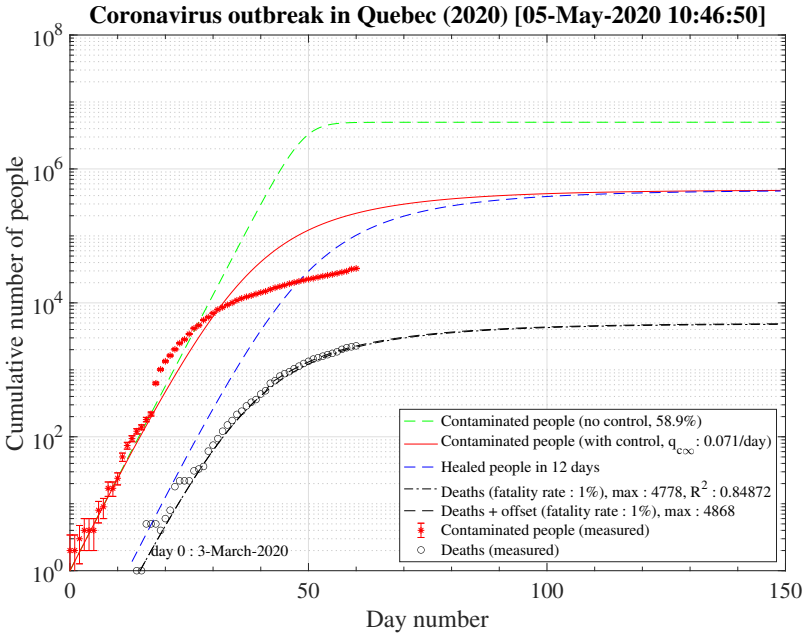

Figure 75: Number of contaminated and dead people by the coronavirus outbreak in Quebec.

- **26-28th of March**: jump in the data... strange ! To be followed if this correspnds to an acceleration of the outbreak
- **29th of March**: The jump is explained by new counting procedure, and the possible arrival at Montreal of people from winter vacations. The evolution remain similar to the predicted one by the model.
- **31th of March**: The number of deaths is increasing as expected initially from the parameters.
- **1st-3rd of April:** An apparent small slowing-down of the daily number of deaths. To be confirmed, regarding the low level.
- **4th of April:** no data available.
- **6-8th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.5$, $q_{c\infty} = 0.3$, while $\tau_{ref} = 2$ and $\triangle\tau = 4$.
- **9-13th of April:** Optimized simulation parameters $q_{c0} = 0.4$, $q_{c\infty} = 0.05$, while $\tau_{ref} = 32$ and $\triangle\tau = 6$, for the slight slowing-down of the number of deaths.
- **14th of April:** Optimized simulation parameters $q_{c\infty} = 0.046$.
- **15th of April**: complicated situation, with a strong increase of the number of deaths with people in intensive care unit decreases. Therefore optimization of the parameters is not done yet.

3.9.4 Sweden

- **26th of March**: A fast rise of the outbreak is observed as in other countries, followed by a sudden sharp change in the growth of certified cases, while the number of deaths is still increasing fast. This is an interesting case where there is likely a change in the policy of testing possible sick people. It cannot arise from a change of the contamination by simple social distancing (incubation time). Initial simulation parameters (high fatality

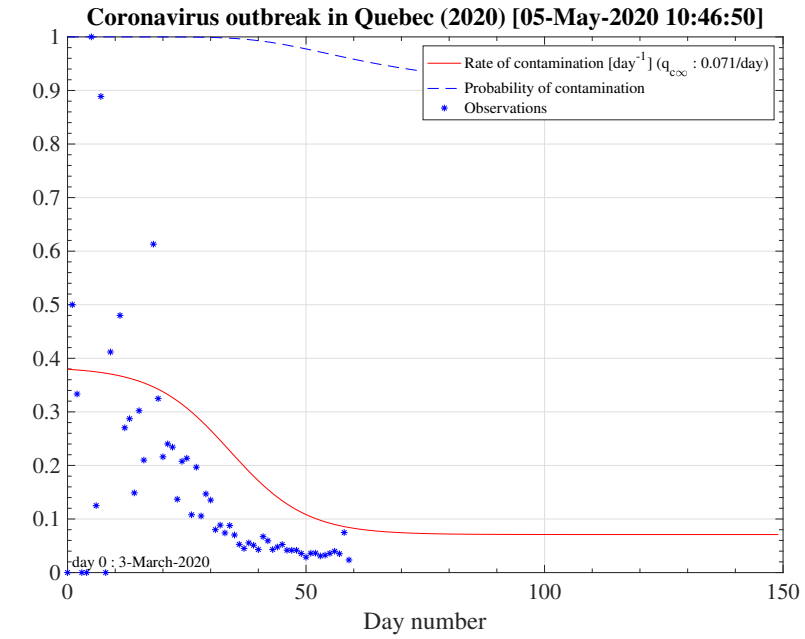

Figure 76: Contamination rate per day and per person and probability of contamination.

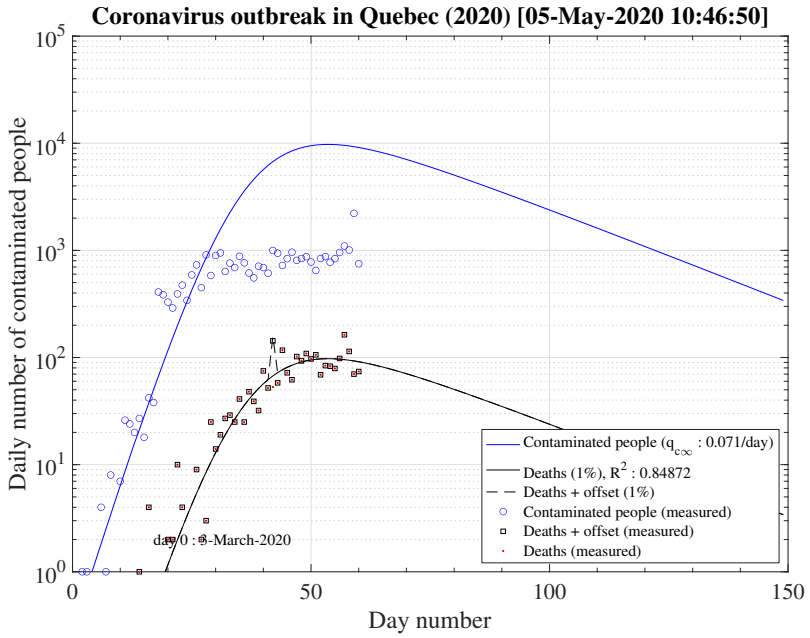

Figure 77: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

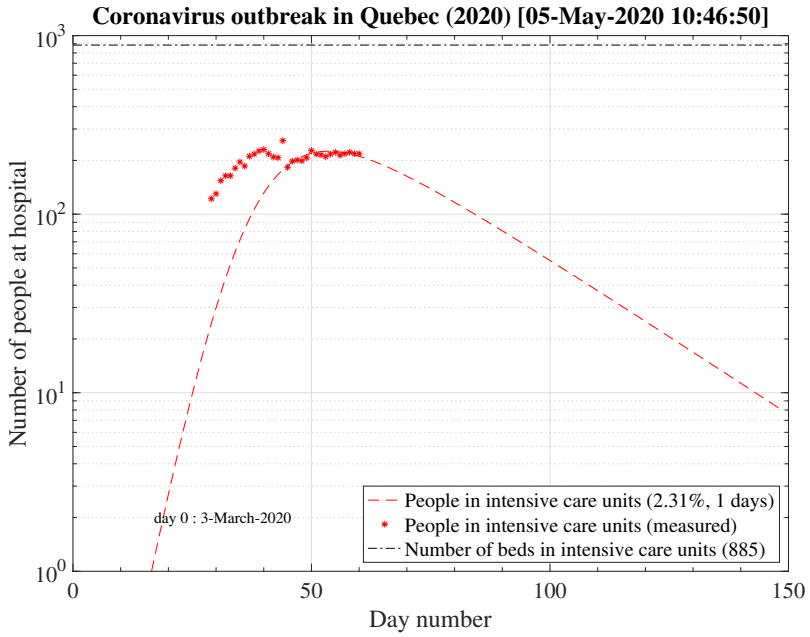

Figure 78: Number of people in intensive care units, fraction of the contaminated people, and additional delay, thanks to recovery time. High fatality rate scenario.

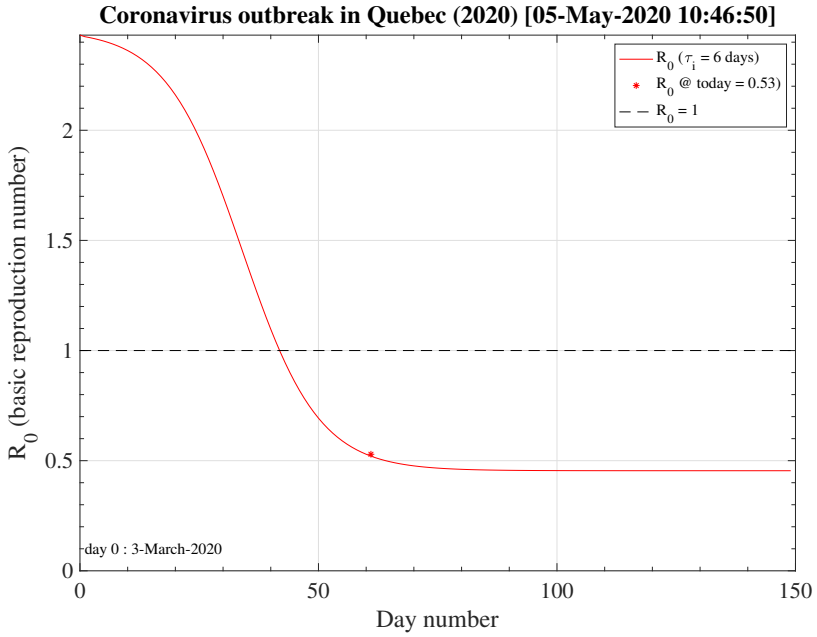

Figure 79: Evolution of the basic reproduction number R_0. High fatality rate scenario.

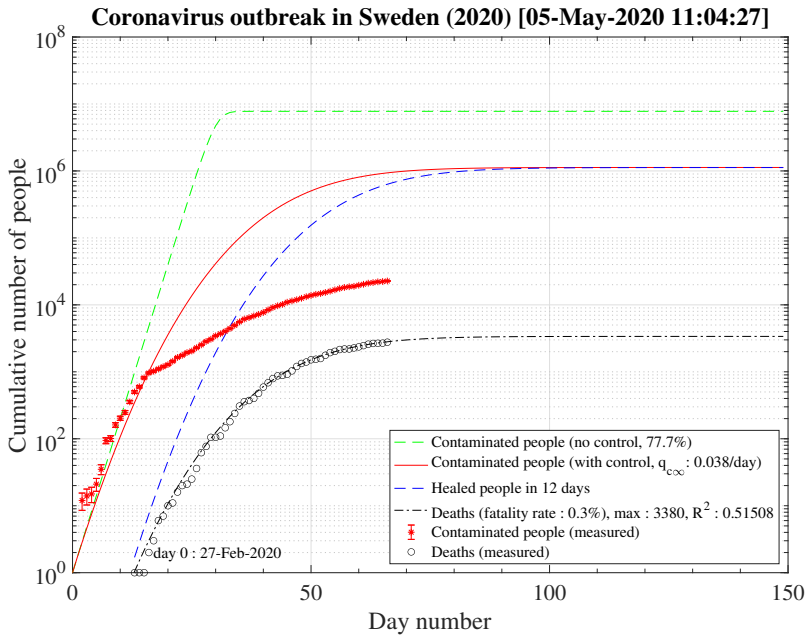

Figure 80: Number of contaminated and dead people by the coronavirus outbreak in Sweden.

rate scenario) are $q_{c0} = 0.8$, $q_{c\infty} = 0.4$, with $\tau_{ref} = 2$ and $\triangle\tau = 5.0$. After day 15, they are $q_{c0} = 0.44$, $q_{c\infty} = 0.31$, with $\tau_{ref} = 0$ and $\triangle\tau = 1.0$. The fatality rate is low $\delta_d = 0.3\,\%$. All results can been seen in Figs. largeur808182.

- **27-28th of March**: Similar evolution for the number of deaths. The cumulated number of contaminated people is totally out.
- **29th of March**: strange change of slope in the total number of deaths, as if it was almost totally stopped...
- **30-31th of March**: the number of deaths is increasing fast again, and follow globaly the trend given by the initial simulation parameters.
- **1st-3rd of April:** Unchanged trend
- **4th of April:** significant slowing-down or statistical noise. Coming days will give more details. Simulation parameters are kept unchanged
- **5th of April**: slowing down observed. better general fit of deaths number by following simulation parameters : $q_{c0} = 0.7$, $q_{c\infty} = 0.1$, with $\tau_{ref} = 2$ and $\triangle\tau = 14.0$. It works for all days. The outbrea peak is for the 7th of May.
- **6-8th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.7$, $q_{c\infty} = 0.1$, while $\tau_{ref} = 2$ and $\triangle\tau = 14$.
- **9-13th of April:** $q_{c\infty} = 0.11$
- **14-15th of April:** Optimized simulation parameters $q_{c\infty} = 0.105$.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

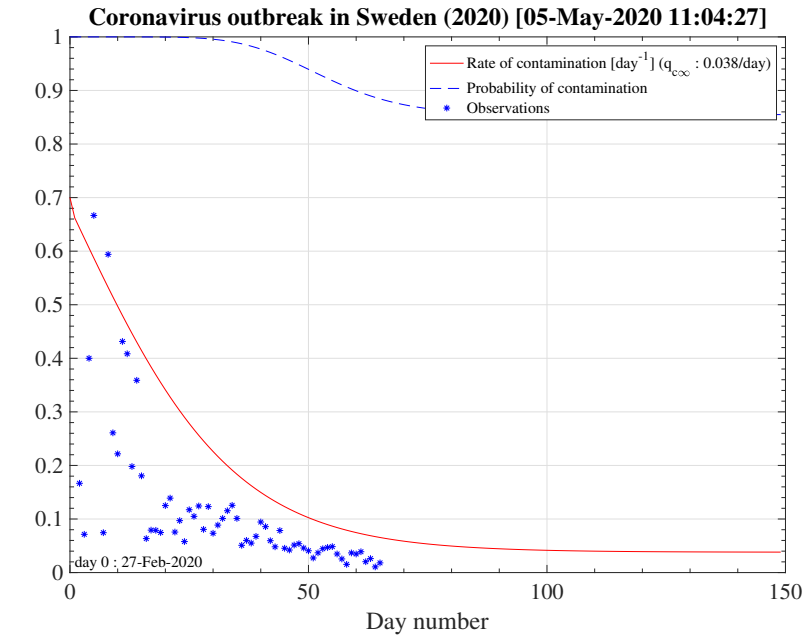

Figure 81: Contamination rate per day and per person and probability of contamination.

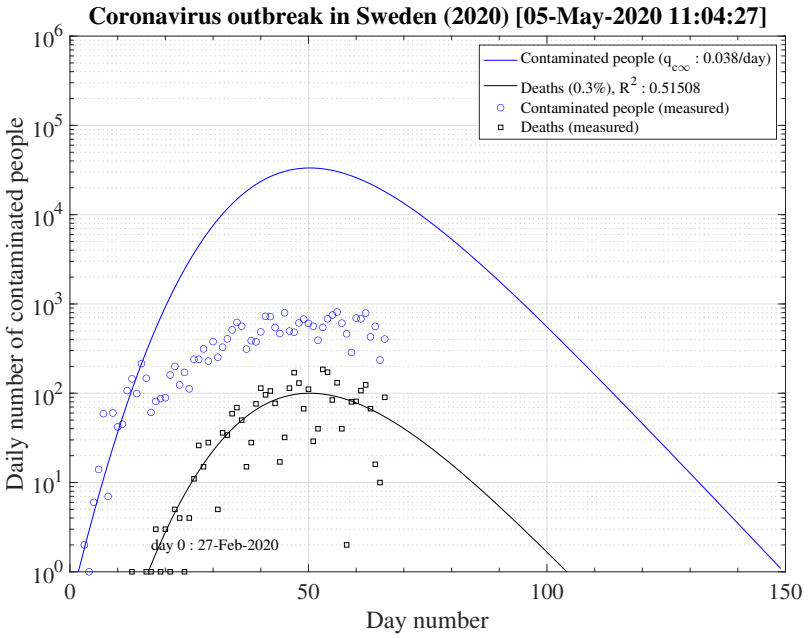

Figure 82: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

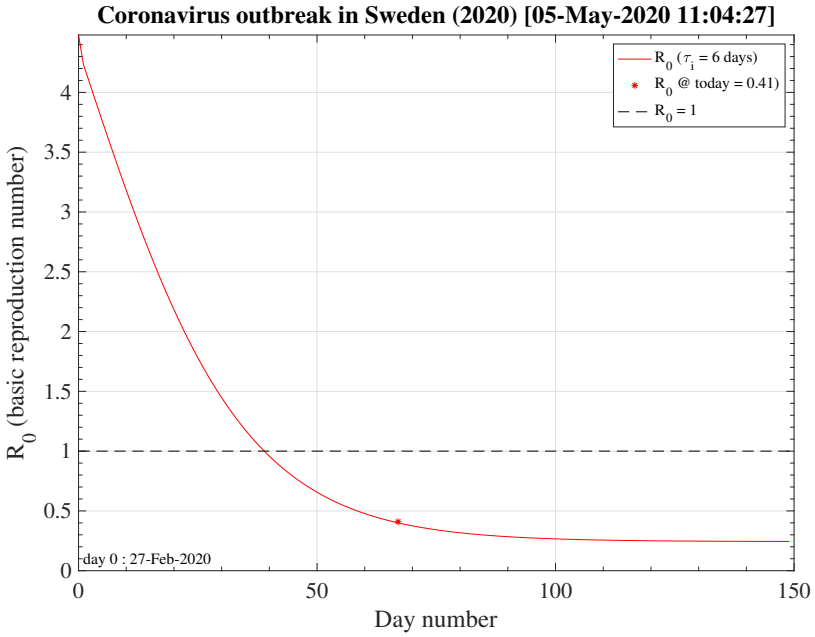

Figure 83: Evolution of the basic reproduction number R_0. High fatality rate scenario.

3.9.5 Netherlands

- **1st-2nd of April:** A fast rise of the outbreak is observed as in other countries. Initial simulation parameters (high fatality rate scenario) are $q_{c0} = 0.8$, $q_{c\infty} = 0.24$, with $\tau_{ref} = 5$ and $\triangle\tau = 8.0$. The fatality rate is low $\delta_d = 0.5\,\%$. All results can been seen in Figs. largeur848586.
- **3rd of April:** Slight slowing-down. New simulations parameters for a better fit are $q_{c0} = 0.9$, $q_{c\infty} = 0.10$, with $\tau_{ref} = 6$ and $\triangle\tau = 10.0$.
- **4-5th of April:** unchanged trend.
- **6-8th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.91$, $q_{c\infty} = 0.1$, while $\tau_{ref} = 6$ and $\triangle\tau = 10$.
- **9-15th of April:**$q_{c\infty} = 0.06$ and $\triangle\tau = 11$.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

3.9.6 Lebanon

- **1st-2nd of April:** The country was setting up rapidly a strong quarantine for all the country. So the number of certified cases is progressively slowing down. Initial simulation parameters (high fatality rate scenario) are $q_{c0} = 0.5$, $q_{c\infty} = 0.11$, with $\tau_{ref} = 4$ and $\triangle\tau = 6.0$. The fatality rate is low $\delta_d = 2.5\,\%$. All results can been seen in Figs. largeur888988
- **3rd-4th of April:** Unchanged trend.
- **5th of April:** in order for a better account of the time evolution of the number of deaths, simulation parameters are modified accordingly : $q_{c0} = 0.45$, $q_{c\infty} = 0.04$, with $\tau_{ref} = 8$ and $\triangle\tau = 13.0$, and the fatality rate is lower $\delta_d = 0.7\,\%$.

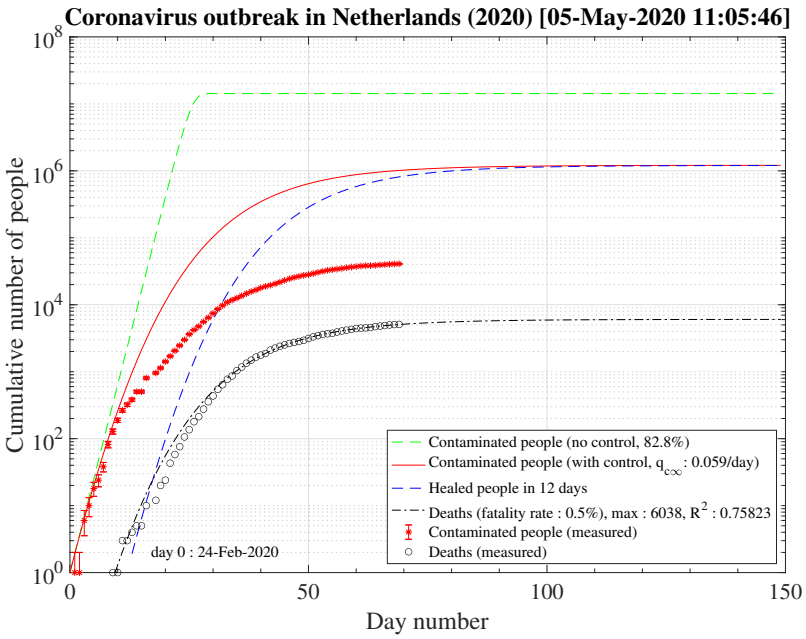

Figure 84: Number of contaminated and dead people by the coronavirus outbreak in the Netherlands.

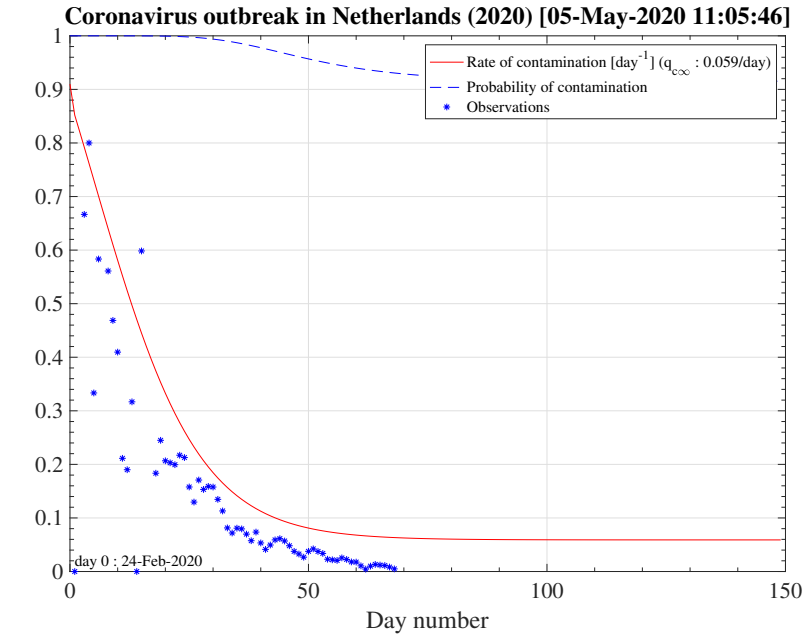

Figure 85: Contamination rate per day and per person and probability of contamination.

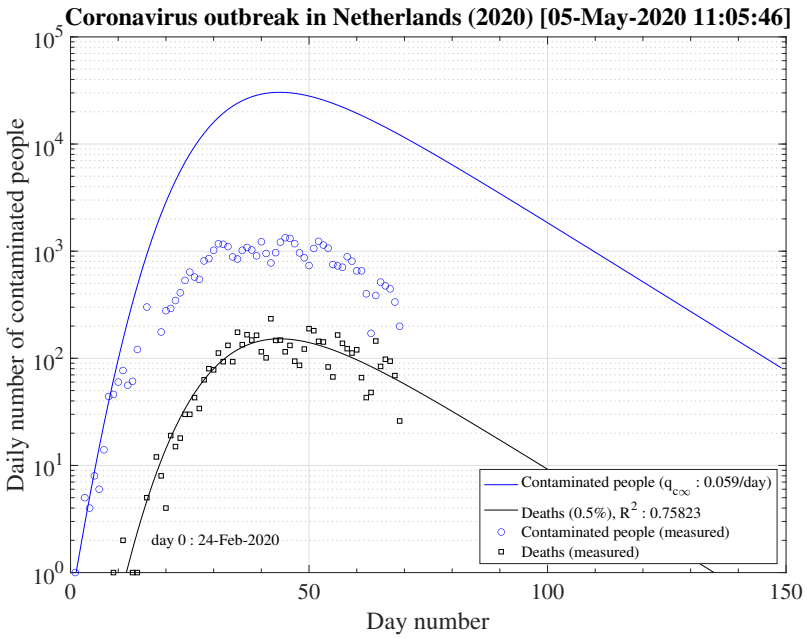

Figure 86: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

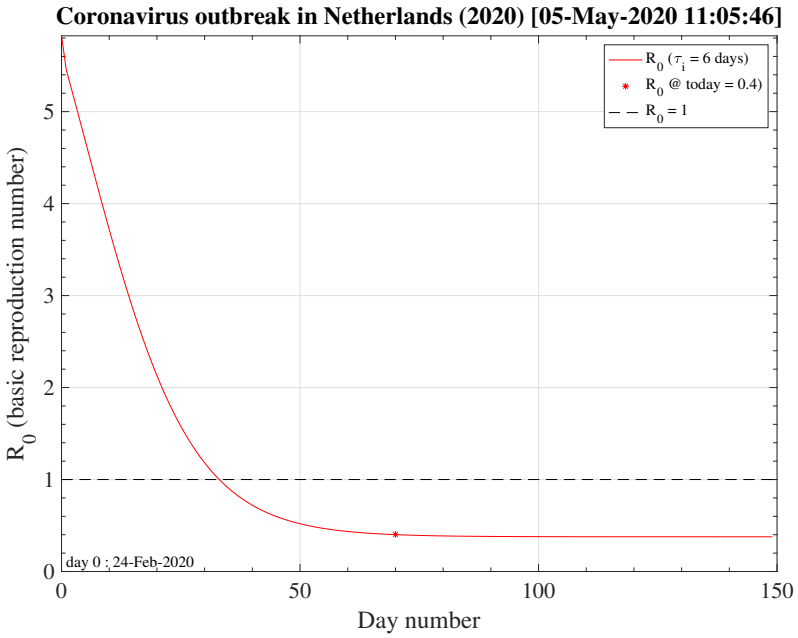

Figure 87: Evolution of the basic reproduction number R_0. High fatality rate scenario.

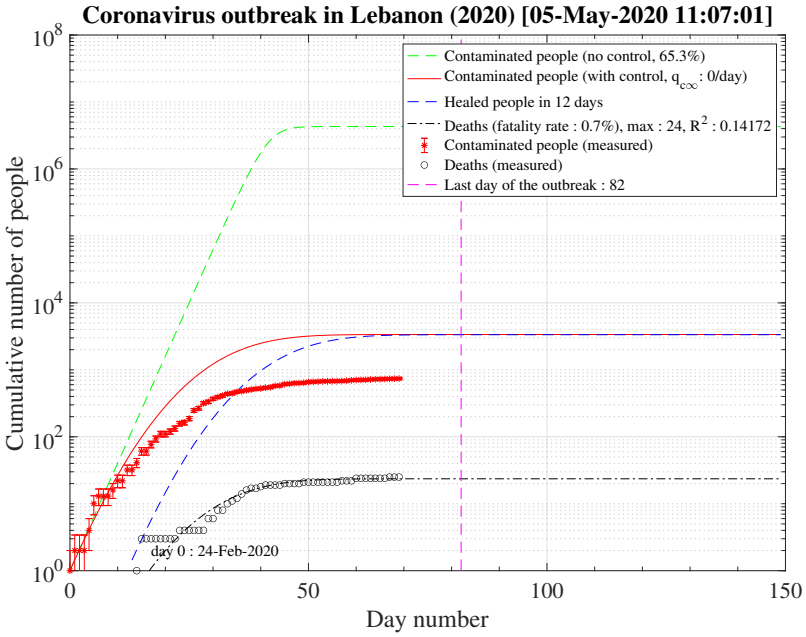

Figure 88: Number of contaminated and dead people by the coronavirus outbreak in Lebanon.

- **6-15th of April:** Incorporation of N_d in Eq.2. New simulation parameters $q_{c0} = 0.45$, $q_{c\infty} = 0.04$, while $\tau_{ref} = 8$ and $\triangle\tau = 13$.
- **16th of April**: simulations parameters are determined from now on by non-linear fit of the daily number of deaths. Several options regarding the number of parameters that may be adjusted, $q_{c\infty}$ alone, $q_{c\infty}$and τ_{ref}, $q_{c\infty}$,τ_{ref} and $\triangle\tau$ and finally all parameters. Usualy, once th peak is passed, only$q_{c\infty}$alone or $q_{c\infty}$and τ_{ref} mays vary significantly.

4 Data analysis

4.1 Comparison between simulations parameters and determination of R_0 factor

Global data analysis gives interesting trends about the outbreak, and how it has been managed by various countries. All main parameters are summarized in Table 1. Those who are able to reach a residual contamination rate $q_{c\infty} < 0.05$ by quarantine or other techniques have a large chance to control the outbreak in a finite time (less than four months) with a small number of people contaminated, and also, by consequence a small number of deaths. This concerns China and South-Korea at present time. Iran seems to be in the good direction though it has to be confirmed. All other studied countries have an uncontrolled evolution of the outbreak, despite what is claimed in the media, with the actual data. This may change, but it has to be demonstrated !

The initial contamination rate in most countries is similar, thanks to the difficulty to get accurate numbers and the statistical uncertainty (low level of number of confirmed cases in some countries). Its mean value is $\bar{q}_{c0} \simeq 1$ approximately, which means that a single person that is contaminated can contaminate about one person per day approximately. This corresponds to a $R_0 \simeq 3.4 \pm 0.9$, excluding Italy, with the incubation time of $\tau_i = 4$ days that is here considered. It can be compared to first estimations using different type of codes, as shown in Fig. 92 [4]. Of course, the estimation of R_0 is highly sensitive to the incubation time τ_i. If it is lowered, a lower R_0 is found. There is a rather large controversy in the recent litterature on this point [4, 5, 6].

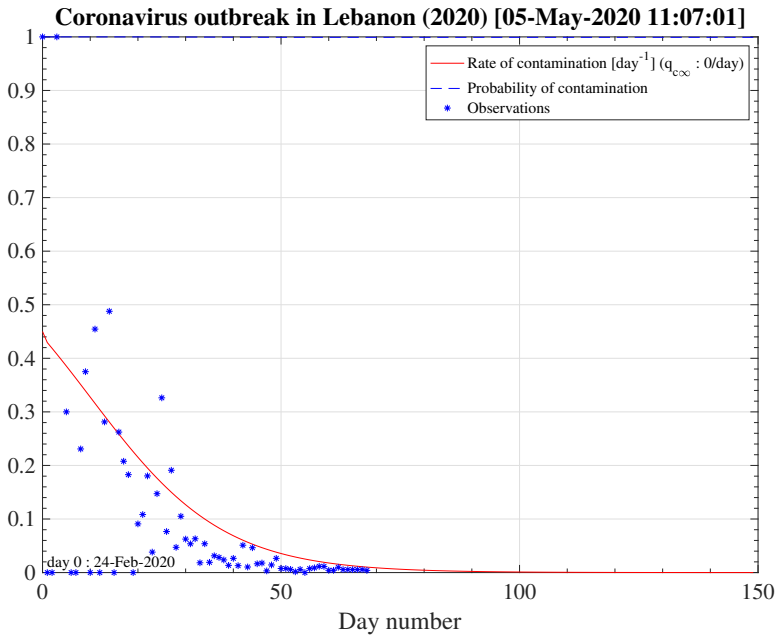

Figure 89: Contamination rate per day and per person and probability of contamination.

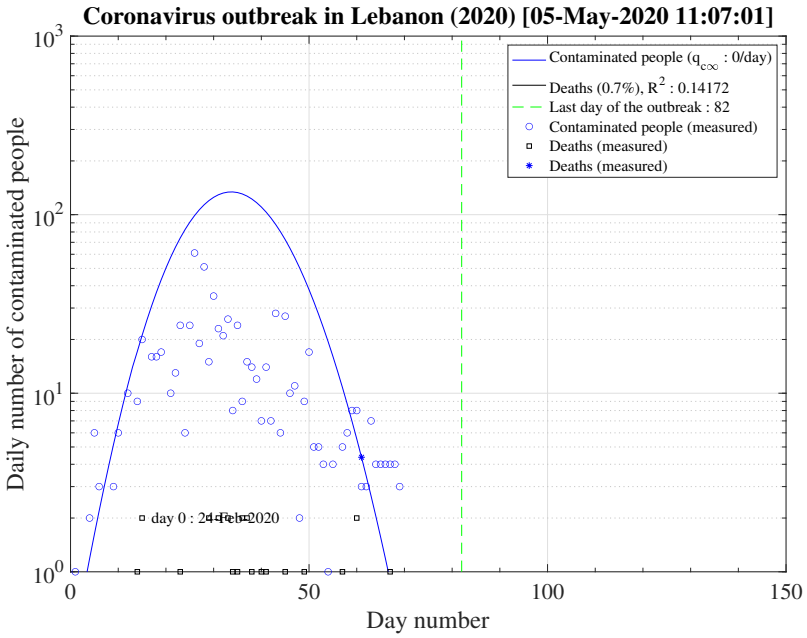

Figure 90: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

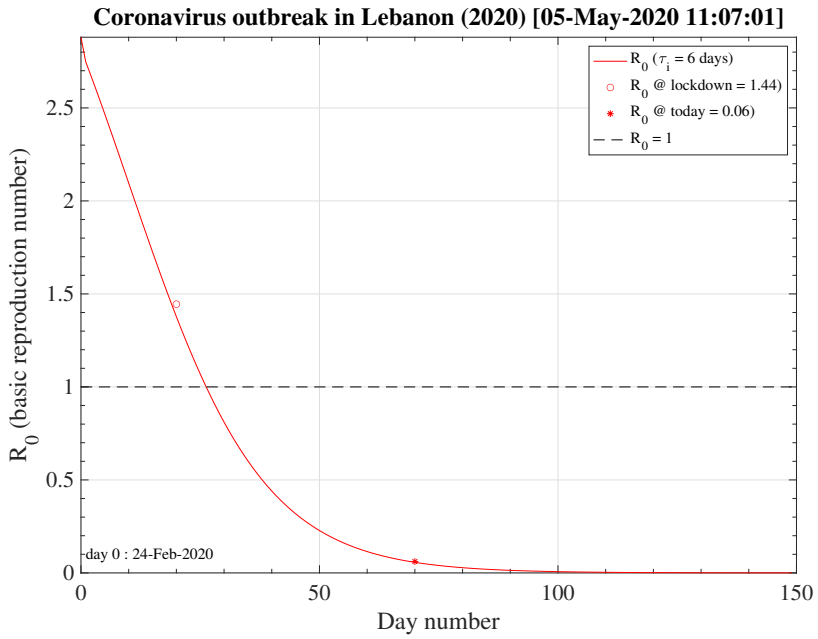

Figure 91: Evolution of the basic reproduction number R_0. High fatality rate scenario.

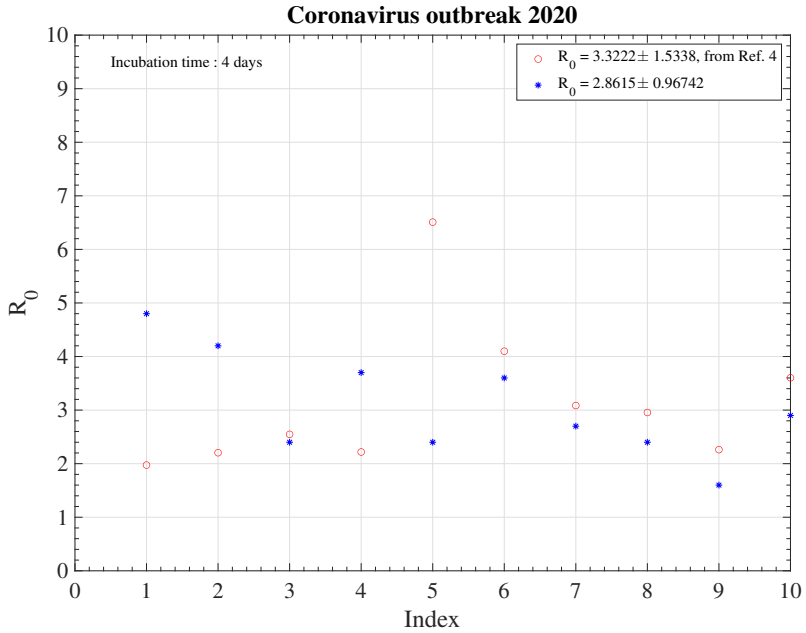

Figure 92: Values of R_0 from Ref. [4] and from studied countries using the present model (see Table 1). Seasonal flu is about one.

	R_0	f[%]	q_{c0}	$q_{c\infty}$	τ_{ref}	$\triangle\tau$	δ_d	Control
China	4.8	79	1.2	0.05	2	8	4	Yes
South-Korea	4.2	76	1.05	0.01	$4+24$	4.5	0.7	Yes
Italy	2.4	66	0.6	0.047	23	10	4.0	Yes
Iran	3.7	73	0.93	0.05	4	10	3.0	Yes
Spain	2.4	66	0.6	0.045	27	6	2.5	Yes
Netherlands	3.6	72	0.91	0.06	6	11	0.5	Yes
France	2.7	62	0.67	0.02	3	18	2.5	Yes
Switzerland	2.4	58	0.6	0.05	4	15	2.0	Soon
USA	1.6	36	0.385	0.01	33+17	7	1.5	Soon
Germany	2.9	66	0.73	0.06	2+30	16	0.1	Soon
United-Kingdom	2.1	51	0.51	0.03	33+22	11	1.0	Soon
Sweden	2.8	64	0.7	0.11	2	14	0.3	Soon
Québec (Canada)	1.6	37	0.4	0.05	32	6	1.0	No

Table 1: Comparative table of coronavirus outbreak simulation parameters between studied countries for the high fatality rate scenario. Parameters that may evolve slightly are those giving best fit of observations at the date of the 9th of April 2020. The basic reproduction number R_0 of the Diamond Princess is 2.9 while from all studied countries $R_0 \simeq 2.86 \pm 0.96$ ($\tau_i = 4$ days)By comparison, the R_0 of the seasonal flue is $1.0 - 1.5$ and of the measles $12 - 18$ (Source Wikipedia).

The seasonal flue is much less (five times, which is the reason of the danger of this outbreak) and it is about 2 times larger than the Spanish flue [7]. It remains nevertheless three times less than the measles $R_0 = 12 - 18$ (Source Wikipedia). After, thanks to the quarantine or the natural reaction of the population becoming cautious, it drops down quite rapidly to lower values. The delay τ_{ref} is rather similar for all countries, except for Italy, that was fast despite the bad actual situation, and Iran which was very late. The rate of decrease is similar is most countries, but twice lower in Asia. This latest parameter indicates the effectiveness of the reduction of the contamination rate.

As shown Table 1, the fatality rate never exceeds $\delta_d < 4\,\%$, though a degradation seems to occur Italy after the 9th of March 2020. But this may arise from a bad evaluation of the confirmed cases. In Iran, after an initial fatality rate that seems totally over-estimated, it reaches the standard level, about $\delta_d = 3.0\,\%$. This evolution is clearly seen for Spain, Italy.

It is common to hear that official figures are false or biased. This is unlikely, as for some countries, since different sources give same results. In addition, simulation parameters are rather similar, whatever the country. The consistency between the number of confirmed cases and deaths, whose ratio in addition is independent of time is also an indication of the robustness of the data. Nevertheless, different policies exist between countries, as well as techniques to identify unambiguously people that are contaminated or died from coronavirus. The error bars on data is certainly much larger than the level from Poisson's statistics, is is related to the test methods uncertainty to identified people that are effectively infected by the coronavirus. Details mays be obtained here.

From the determination of R_0 it is possible to estimate the fraction of the population that must be immunited to stop the outbreak. It can be done by vaccine or naturally. Data using Eq. 11 are given in Table 1. It is interesting to not that this fraction is 33 % for the seasonal flu, and 95 % for the measles, thanks to their respective basic reproductive number.

4.2 Interpretation of the fatality rate

4.2.1 General analysis

As shown in the calculations, the mortality rate is varying significantly between countries (see Fig. 93), in particular within Europe where health care systems are similar. The increase of δ_d with time is a sign that the statistics of confirmed cases is becoming progressively wrong as the outbreak develops. This justify why δ_d of the cruise liner Diamond-Princess is likely the only robust value and the two scenarii that will be discussed below.

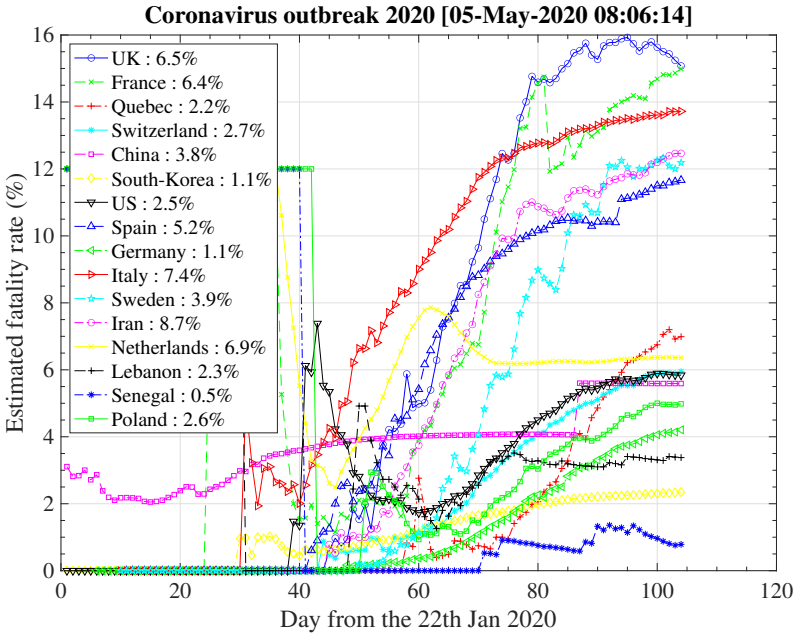

Figure 93: Fatality rate as function of time starting from 22th of January 2020. The mean value of the fatality as a function of time is indicated in the figure caption. The increase of δ_d with time is a sign that the statistics of confirmed cases is becoming progressively wrong as the outbreak develops. This justify why δ_d of the cruise liner Diamond-Princess is likely the only robust value.

It is known that old people are much subject to death than young people, by more than two orders of a magnitude from a Chinese study based on 45000 persons. According to this study, the mean mortality rate is between 2.3 %, but 0 % for children les than 10 years old, 0.2 % like the flu (twice more precisely) for people less than 39 years old, 0.4 % for the forties, 1.3 % between $50-59$ years old, 3.6 % for the sixties, and 8.0 % for the for octogenarians and beyond likely 15.0 % (see Fig. 94) [6]. In addition, two third of the deaths arised from men, and this pulmonary fragility is likely linked to tobacco consumption . The role of co-morbidity may play likely a very significant contribution to the fatality rate. Indeed, the case of the cruise liner Diamond Princess is enlightening on this point of view. With about 4000 passengers onboard, 705 (after landing a bit less, with 696 confirmed contaminated people) of them where unambiguously diagnosed as contaminated, and only 7 deaths have been recorded. This corresponds to $\delta_d = 1.0\,\%$, close to the value in South-Korea (at the beginning of the outbreak), where broad test campaigns have been carried out. Since this population was rather old, and one can suppose that it was in rather good health to do the trip, δ_d is much lower than standard estimates in many countries, and disagree with analysis that claims a strong age-dependence of the fatality rate. Therefore, a possible interpretation as follow: δ_d is around 1.0 % for people in good health, what ever the age above 50 years old (less for younger people), and larger mean δ_d may arise from a underestimate of the actual number of people contaminated (sampling is done more than and full effective measurement), except in South-Korea, together with the age dependence of the fatality due to co-morbidity. So already weak people suffering from serious illness are much more sensitive to the effect of the virus. an indication of the role played by co-morbidity is the fact that men and women in China are almost equally contaminated (slightly more men), but 2/3 of very sick people dying are men. It may be the consequence of the poor lung condition of Chinese men who are known to smoke a lot.

This interpretation leads to to approach :

- **High fatality rate scenario** in which the number of contamined people officialy declared is trusted, and the fatality rate is the observed ratio between the number of contaminated people and the deaths. It is accepted in this scenario that the fluctuation of the contam-

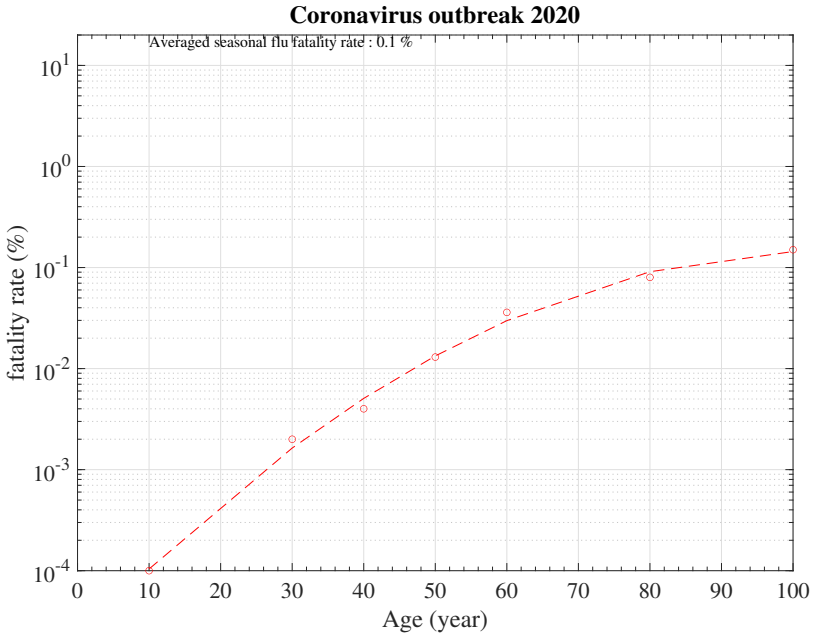

Figure 94: Mortality rate as function of the age [6].

ination rate between countries may arise from the fraction of old people that are already sick, thanks to the large dependence of the fatality rate, and their involvment in the active social life, so subject to a high risk of contamination in this case.

- **Low fatality rate scenario**, in which the fatality rate is fixed and estimated to $\delta_d \simeq 1.0\,\%$ approximately (from consistent South-Korea and cruise liner Diamond Princess data anlaysis), and the number of contamined people officialy declared is just the result of an inaccurate sampling of the population with a high probability to be sick. In that case, the number is the deaths is the single reference, and the actual number of effective contaminated people is hidden. This approach will require a larger rate of contamination qc to reproduce the observations as compared to the standard one. Ultimately, it will change significantly the amplitude and time at which the outbreak will peak, and the total number of deaths, as compared to the standard case. An interesting study on the actual number of contaminated people at Wuhan where the outbreak started gives some indications [7].

4.2.2 The case of the cruise liner Diamond Princess

The cruise liner Diamond Princess has been contaminated around the 1st of February 2020, and the outbreak spreads rapidly onboard. It was placed in a strong quarantine near Yokohama in Japan, and all passengers where forced to stay in their cabins during more than two weeks approximately. The 3711 passengers + crew where all tested against the contamination by the coronavirus, and ultimately, 705 where diagnosed positive (after landing a bit less, with 696 confirmed contaminated people). Seven people died, so $\delta_d = 1.0\,\%$. A shown in Fig. 95 the outbrak started very quickly, like in countries, but thanks to the strict quarantine, it slowed down rapidly and the $q_{c\infty}$ felt down to 0.02, like in countries which succeeding in the control of the outbreak. The outbreak was controled in the cruise liner in 26 days. The outbreak never reach the 60 % saturation level, and without quarantine, 34 passengers would have died. The reservoir effect, though significant, remains less than 20 %, thanks to the effectiveness of the quarantine (Fig. 96). Simulations parameters are: $q_{c0} = 0.72$, $q_{c\infty} = 0.02$, with $\tau_{ref} = 12$ and $\triangle\tau = 2.0$. Since τ_{ref} is large, it means that the reaction of the crew was rather late, concerning the danger of the outbreak inboard. The daily number of sick people is given in Fig. 97.

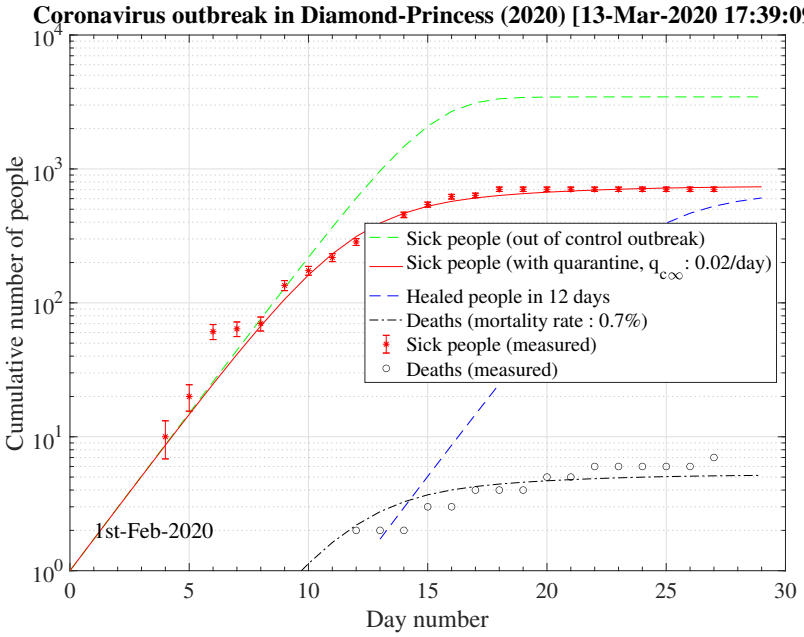

Figure 95: Number of contaminated and dead people by the coronavirus outbreak in the cruise liner Diamon Princess. The number of diagnosed passengers is in this case exactly known. The estimated fatality rate is $\delta_d = 1.0\,\%$, for a rather old but in good health finite population.

This case is particularly interesting because it shows unambiguously the effectiveness of a strict quarantine. The residual contamination rate must be lowered less than $q_{c\infty} = 0.02$ to successfuly control and stop the outbreak. This result is fully consistent with calculations for China and South-Korea. None of the other countries have reach this level, and therefore will control the outbreak at the date of the 14th of March. Moreover, the air-conditioning system has not spread the virus, otherwise the outbreak would have been out of control in this closed volume. This is an important result, that clearly highlight the importance of the close contacts for oral contamination or possibly the contamination by skin contacts. Wearing gloves can be an important test to prevent the spread of the virus, given that it seems to last a long time on surfaces.

The low fatality rate $\delta_d = 0.7\,\%$ while the mean age of the passengers was above 50 years old, but in rather good health to do the trip is a sign that co-morbidity may be the reason for strong age dependence of the fatality rate, as suggested by the Chinese study. This number is closed to the value estimated in South-Korea, which performed a broad control of its population and not a random sampling that is likely done in many countries, by failure of the health care system, or by lack of available tests.

From this analysis, and South-Korea data, a low fatality rate scenario is described as indicated in Sec. 4.2.1, and will be applied to all countries suffering the outbreak that have been studied. From the high and low fataility rate scenarii, it will give some reasonable limits on the development of the outbreak, on its end date and on the ultimate total number of deaths that is expected.

4.2.3 Ultra low fatality rate scenario: the COVID-19 is like the seasonal flu

The possibility that the number of contaminated persons could have been very strongly underestimated is studied. In order to reproduce the outbreak, and considering that only the absolute number of deaths matters (low fatality rate scenario), with the fatality rate of the seasonal flu, $\delta_d = 0.1\,\%$, and considering in addition that the contamination rate is so high that the outbreak is totally out of control since the beginning, one must consider the following simulations parameters : $q_{c0} = q_{c\infty} = 0.45$ to reproduce observations as shown in Fig.98. In that case the

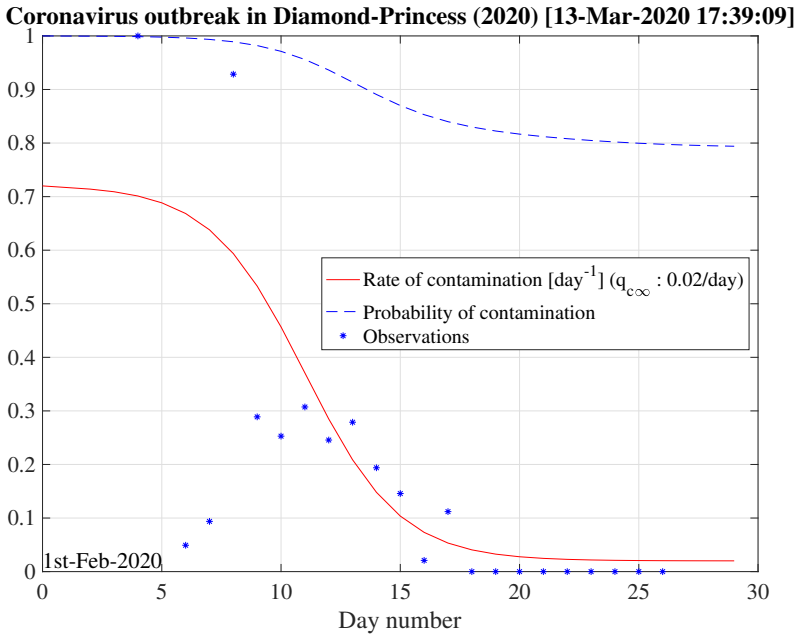

Figure 96: Contamination rate per day and per person and probability of contamination.

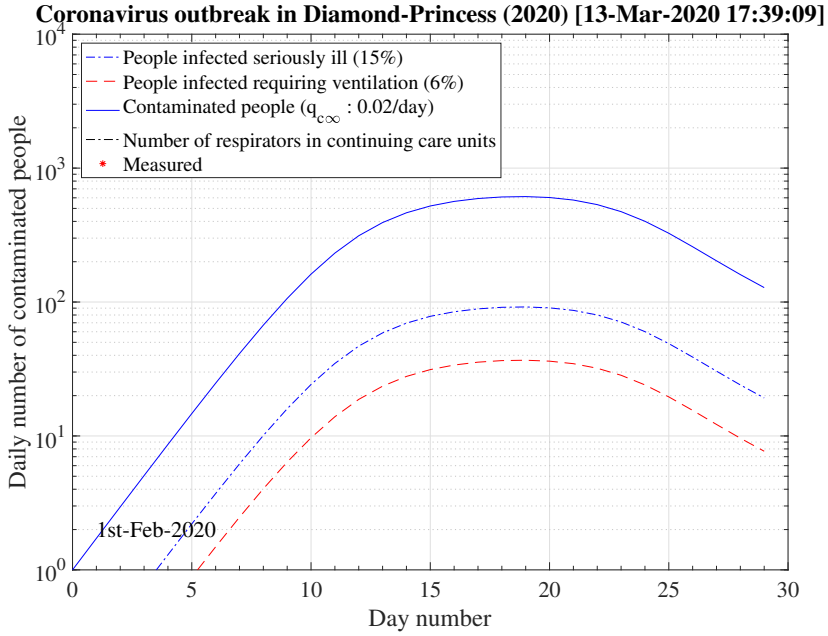

Figure 97: Estimated number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation for the COVID-19 outbreak in the cruise liner Diamon Princess.

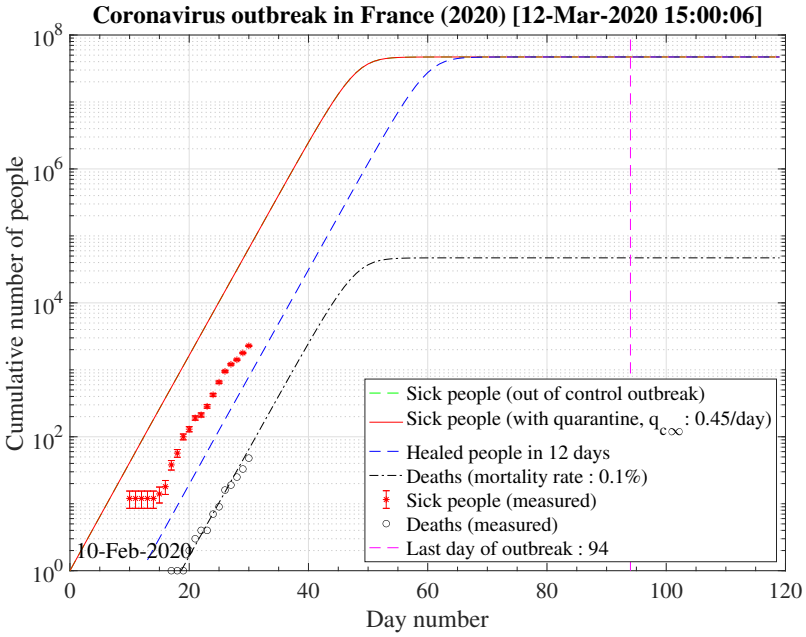

Figure 98: Number of contaminated and dead people by the coronavirus outbreak in France, if the number of deaths is the data of reference, considering that the fatality rate is 0.1 % like for the seasonal flue.

domestic outbreak should have started 10 days before the bifurcation of the number of official contaminated cases, at around the 10th of February 2020. If such a situation is true, it means that all the french population will become immunited in almost 40 days, and after 53 days the outbreak should naturally slow down, as shown in Fig.99 and a decrease of the number of daily deaths should be also observed. The outbreak would have led to up to 47000 deaths in this simulation, which is quite significant as compared to the seasonal flue but much less than the standard approach, based on both numbers: contaminated people and deaths. The difference with the seasonal flu arises from the rate of contamination that must be much higher for the coronavirus to reproduce the growth rate of the number of deaths. Interestingly, the number of people which require active ventilation in continuous health care units must be lowered to $\delta_{vsv} = 0.6\,\%$ in this case to be approximately to the level of actual observations. But thanks to the simulation, this number should break very quickly the threshold of the number of available respirators, thanks to the large rate of contamination to reproduce the number of deaths (at day 34, so at the date of the 15th of March 2020). The slope in time is not well reproduced, since calculated $N_{vsv}\,(t)$ must grow less quickly than observations. At the date of the 11th of March, 2281 confirmed cases have been officialy reported, while the effective number of cases should be more than 65000 ! A considerable difference effectively, but noboday can confirm this hidden number.

In anycase, whatever the approach, the overload of the hospitals will come soon and even sooner if the number of contaminated people is deeply underestimated, considering the COVID-19 outbreak like a standard flu outbreak.

4.3 Statistical analysis of the time evolution of the cumulative number of deaths

Statistical analysis of the number of deaths in the studied countries has been carried out to test if the time sequence for each country is similar or not. As shown in Fig. 100 for the countries which do not exhibit a soon occurence of an outbreak peak, the exponential growth rates are very similar, and the mean value is about $\tau_D = 2.74 \pm 0.52$ days. When data of these countries are normalized to the highest value (Spain, the 28th ofMarch), the exponential growth rates

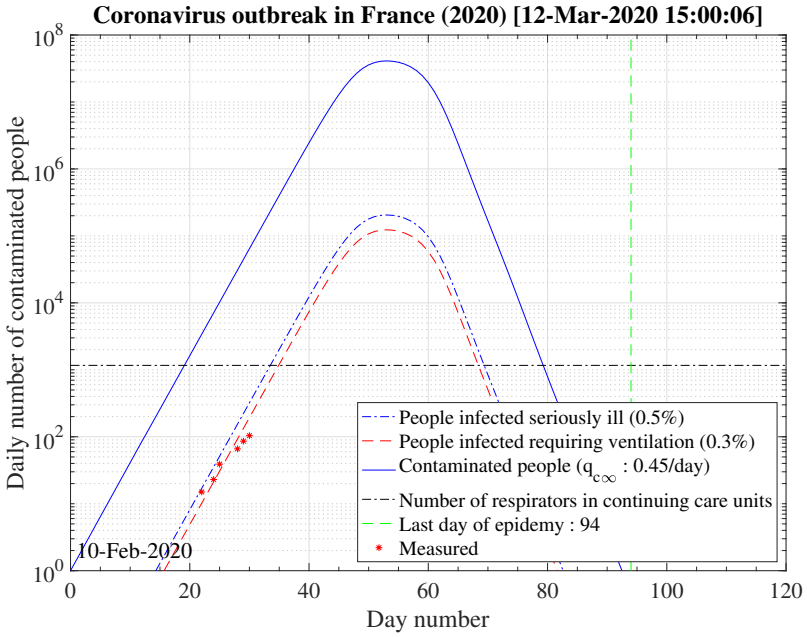

Figure 99: Number of contaminated people, and seriously sick people, and those requiring continuous artificial ventilation.

are very similar too. From the fit of all data, the doubling time is about $\tau_D = 2.87$ days.

For countries that have past the outbreak peak, or are close to it, as shown in Fig. 101, the doubling time is estimated from the first few days. The mean doubling time is shorter if 6 days are considered, $\tau_D = 1.98 \pm 0.21$, but compatible to previous estimations within error bars. When 8 days are onsidered, it becomes $\tau_D = 2.59 \pm 0.65$ days.

So, even of the fatality rates vary on two orders of magnitude, the time suite of data concerning the cumultaive number of deaths is totaly consistent for all countries. The reference is about the doubling time is $\tau_D = 2.69 \pm 0.54$ days.

The mean contamination rate from time evoluton of the cumulative number of deaths may be easily obtained in the approximate limit

$$\ln\left((q_{c0}\Delta t + 1)^n\right) = \ln\left(2^{n\Delta t/\tau_D}\right)$$

or

$$n\frac{\Delta t \ln 2}{\tau_D} = n\ln\left(q_{c0}\Delta t + 1\right) \tag{54}$$

or

$$\frac{\Delta t \ln 2}{\tau_D} \simeq \ln\left(q_{c0}\Delta t + 1\right) \tag{55}$$

such that

$$q_{c0}\Delta t = \exp\left(\ln 2\Delta t/\tau_D\right) - 1 \tag{56}$$

If $\tau_D \geq 1$, $q_{c0} \leq 1$, and for $\tau_D = 2$, $q_{c0} \simeq 0.41$. The reproduction factor is then

$$R_0 = \tau_i\left(\exp\left(\ln 2\Delta t/\tau_D\right) - 1\right)/\Delta t \tag{57}$$

From the cumulative number of deaths, and taking an averaged value $\tau_i = 7.0$ days from study concerning travellers of Wuhan, $R_c \simeq 2.13$ for $\tau_D \simeq 2.6$,since $\Delta t = 1$ day. This value is lower than the basic reproduction factor $R_o \simeq 2.78$ determined from the early phase of the outbreak, using the cumulative number of contaminated people, but there is large uncertainties from country to country. As shown in the detailed time evolutions, the fast initial rise is usually followed rapidly by slower rate, consistent with the cumulative number of deaths, which becomes more observable later. The value of R_c is larger than 1, so consistently, the epidemy is

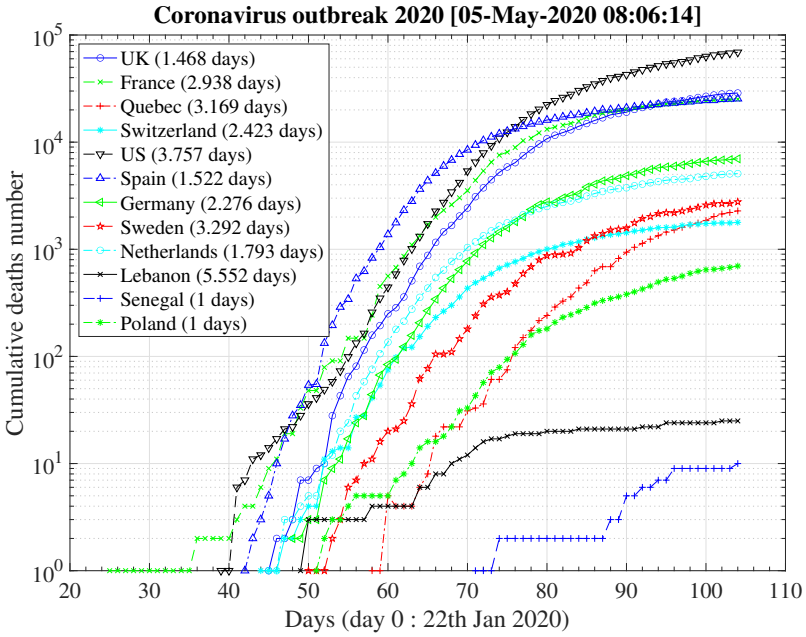

Figure 100: Cumulative deaths number for countries in the early phase of the outbreak (no peak). In figure caption, the doubling time is indicated (all days are considered).

still active in many countries, expect China, South-Korea, Italy and Iran, at the 28th of March. Its value corresponds to $q_{c\infty} \simeq 0.26$. To control the outbreak, $q_{c\infty} \ll 0.25$, and a value of $q_{c\infty} \leq 0.05$ must be targeted.

4.4 Risk evaluation of the COVID-19 outbreak in the world

4.4.1 Coarse estimate

The question of the dynamics of the outbreak is a major issue for an appropriate policy. It can be seen that countries or regions (or cities) with dense populations are the most affected. This is obvious because the probability of interaction between people is higher. The high density case studied are boats (Charles-de-Gaulle aircraft carrier, and Diamond-Princess cruise liner). For comparison in Paris, the density is 12,000 inhabitants / km2. On a boat like the Charles-de-Gaulle, which is 245 m long and 65 m wide, considering 3 bridges, the population density is 1,700 * 1,000,000 / 245/65/3 = 35000 people / km2! No wonder the epidemic is exploding. By way of comparison, in Marseille city, the population density is 3500 inhabitants / km2, therefore much less. In Wuhan, it is 5800 inhabitants / km2 (less than in Paris!), And in New York it reaches 7,100 inhabitants / km2. In Dakar, Senegal, it is like that of Paris, 12,000 inhabitants / km2, while there are only very few deaths ... In Africa, with significant disparities, the population density is generally low, 40 inhabitants / km2 (Europe 73 inhabitants / km2, United States 33 inhabitants / km2, China 148 inhabitants / km2, and India 395 inhabitants / km2) except in Nigeria (Lagos in particular with 21,300 inhabitants / km2). And it is in Lagos capital in Nigeria that there are the most cases! So if population density is an important factor, it is in localized areas where density is extreme that the outbreak spreads the fastest.

However, the question of fatality, which is the essential psychological factor in any outbreak, does not exactly follow the density of the population. In addition the fatality linked to 100% COVID-19 may be subject to discussion, and it is very likely that this fatality is much lower than estimated($< 0.7\,\%$). On the other hand, there is a high proportion of very sick people, and the question is therefore why so many sick people in one country and not in another, with equal population density.

This is where the age pyramid comes in. It is very weighted towards young ages for India, 56% of the population is under 30 years old, while for France, it is uniform and only 37% of

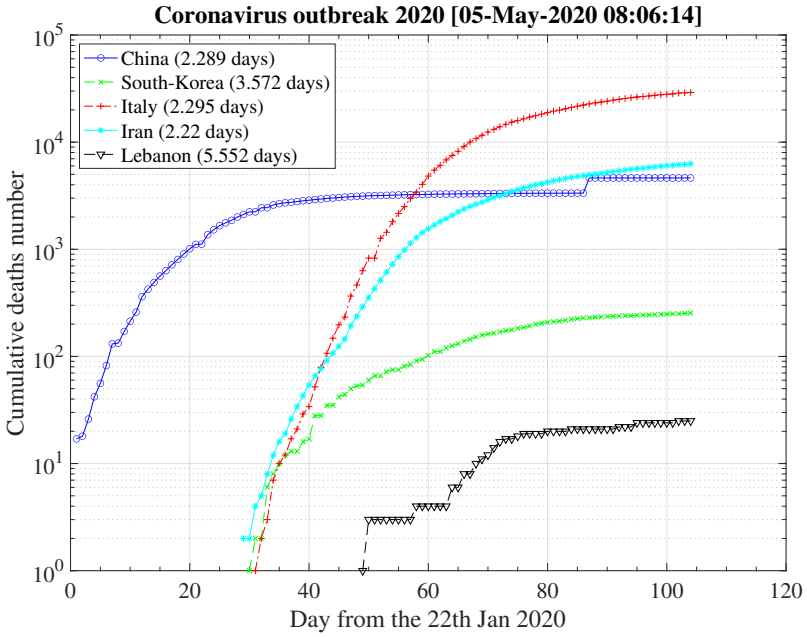

Figure 101: Cumulative deaths number for countries that have past the outbreak peak (China, South-Korea), or approching it. In figure caption, the doubling time is indicated (The 8 first days are considered for the estimation of the doubling time, to avoid the influence of confinement on the result).

the population is under 30 years old! See the link here. In the United States, it is 41%, as in China, which pays a heavy price for the only child! In Africa, the differences are even more marked: Senegal 72% of the population is under 30, the same in Nigeria, 55% in Morocco and Algeria. So, as we know that COVID-19 affects the elderly much more than the young (who can be healthy carriers or slightly ill, 99.8% for those over 30, see the curve in the technical note) it is not surprising that the epidemic remains silent in India and Africa, except in the densely populated regions, where the cases appear a little more like in Nigeria, because this compensates for the low population ratio which can be really affected.

So in summary, COVID-19 is a disease of very dense regions where the fraction of elderly people is high. It is the combination of the two factors that makes the problem acute. So European countries, China, the United States are more affected than Africa and India, except in very localized regions with high population density. In Russia, Moscow, and not the rest of the country for example, with 39% of people under the age of 30. Population density is extremely low elsewhere.

From this analysis, we can extract a criterion on the impact of the COVID-19 epidemic in health terms. This factor Fcovid is the product of (the density of inhabitants / km2) x (the fraction of people over 30 years old). The higher Fcovid, the higher the risk of health damage:

- France -> Fcovid = 0.63 * 105 = 66, Ndécès COVID-19 / 100,000 inhabitants: 1e5 * 19323 / 70e6 = 27
- France, Paris -> Fcovid = 0.63 * 12,000 = 7,650, Ndécès COVID-19 100,000 inhabitants: 1e5 * 1160 / 2.4e6 = 48
- France, Marseille -> Fcovid = 0.62 * 3,500 = 2,170, Ndécès COVID-19 / 100,000 inhabitants: 1e5 * 26 / 0.86e6 = 3
- France, Cantal -> Fcovid = 0.63 * 25 = 16, Ndécès COVID-19 / 100,000 inhabitants: 1e5 * 0 / 1.43e5 = 0

- Sweden -> Fcovid = 0.63 * 23 = 15, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 1511 / 10.2e6 = 14.9
- China -> Fcovid = 0.59 * 148 = 87, Ndécès COVID-19 / 100,000 inhabitants: 1e5 * 4632 / 1393e6 = 0.33
- China, Wuhan -> Fcovid = 0.59 * 5,800 = 3,422, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 3869 / 11.1e6 = 34
- India -> Fcovid = 0.44 * 395 = 174, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 3869 / 1353e6 = 0.28
- Senegal -> Fcovid = 0.28 * 82 = 23, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 3 / 15.8e6 = 0.02
- Senegal, Dakar: Fcovid = 0.28 * 5.500 = 1540, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 3 / 1.05e6 = 0.28
- -Nigeria -> Fcovid = 0.28 * 230 = 64, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 19 / 195e6 = 0.0097
- Nigeria, Lagos -> Fcovid = 0.28 * 21,300 = 5.964, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 13 / 13.8e6 = 0.094
- Lebanon -> Fcovid = 0.49 * 638 = 312, Ndeceased COVID-19 / 100,000 inhabitants: 1e5 * 21 / 6.8e6 = 0.31
- Iran -> Fcovid = 0.49 * 50.27 = 24, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 5031 / 81.8e6 = 6.15
- Iran, Tehran -> Fcovid = 0.49 * 812 = 397, Ndecès COVID-19 / 100,000 inhabitants: 1e5 *? / 8.6e6 =?
- Morocco -> Fcovid = Fcovid = 0.45 * 80 = 36, Ndécès COVID-19 / 100,000 inhabitants: 1e5 * 546 / 36e6 = 1.5
- Morocco, Rabat -> Fcovid = 0.45 * 4873 = 2.193, Ndécès COVID-19 / 100,000 inhabitants: 1e5 * 5 / 0.57e6 = 0.87
- -Algeria -> Fcovid = 0.45 * 18 = 8.1, Ndécès COVID-19 / 100,000 inhabitants: 1e5 * 367 / 42.23e6 = 0.86
- Algeria, Algiers -> Fcovid = 0.45 * 3,700 = 1.665, Ndécès COVID-19 / 100,000 inhabitants: 1e5 * 96 / 7.7e6 = 1.24
- Russia -> Fcovid = 0.61 * 8 = 5, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 313 / 144e6 = 0.21
- Russia, Moscow -> Fcovid = 0.61 * 8300 = 5.063, Ndecès COVID-19 / 100,000 inhabitants: 1e5 *? / 1353e6 =?
- Singapore -> Fcovid = 0.66 * 7842 = 5.176, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 11 / 5.6e6 = 0.19
- United States -> Fcovid = 0.59 * 33 = 19, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 38664 / 328e6 = 11
- United States New-York -> Fcovid = 0.59 * 7,100 = 4,189, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 8893 / 8.4e6 = 105
- Charles-de-Gaulle aircraft carrier -> Fcovid = 0.05 (there are only young people in the crew) * 35,000 = 1,750, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 0/1700 = 0
- Diamond-Princess liner -> Fcovid = 0.7 (because 70% of the passengers + crew are elderly) * 35,000 = 2,4500, Ndecès COVID-19 / 100,000 inhabitants: 1e5 * 7/1700 = 411

Obviously, this coefficient must be calculated rigorously with the age distribution and the mortality rate by age group. But starting from the rough calculations which were carried out above, one notes approximately three large groups:

- group I (Fcovid <100): the epidemic potentially has almost no health impact, and we hardly see any deaths (case of Cantal in France in particular)
- group II (100 <Fcovid <2,500): the epidemic potentially has a moderate health impact (Algiers, Marseille, Dakar, Rabat, Lebanon, Iran, Charles-de-Gaulle aircraft carrier)
- group III (2,500 <Fcovid): the epidemic potentially has a marked to very strong health impact (Paris, Wuhan, Lagos, Moscow, New York, Diamond-Princess liner, Singapore)

So, no surprise on the data, it is the conjunction of a poor age pyramid with a high population density which makes the health risk of COVID-19 potentially high. The cities of countries with the wrong age pyramid are the most penalized. But the situation can be mitigated by rapid management of the epidemic (social distancing), and from this point of view, Sinpagour has managed the epidemic remarkably. The uniqueness of Iran comes only from religious gatherings as in the holy city of Quom. The same phenomenon is found in South Korea, in India (Rajasthan), in France near Mulhouse and in Italy near Bergamo (football match). Gathering 1000-2000 people or more in a limited space is equivalent to reach the density of a boat ... 35,000 people / km2. The explosive potential of these gatherings linked to the density of population is therefore proven. From this point of view, Saudi Arabia, by closing the holy places in Mecca did exactly what was needed.

Finally, it is interesting to correlate the number of deaths from COVID-19 per 100,000 inhabitants with the coefficient Fcovid indicated above. If we do not consider the case of Singapore which is singular because there is a very strict management of people infected from the start, we find an estimate of the linear correlation coefficient of Bravais-Pearson

$$\hat{r}_p = \frac{\hat{\sigma}_{XY}}{\hat{\sigma}_X \hat{\sigma}_Y} \tag{58}$$

where

$$\hat{\sigma}_{XY} = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y}) \tag{59}$$

with

$$\hat{\sigma}_X = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \tag{60}$$

$$\hat{\sigma}_Y = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - \bar{y})^2} \tag{61}$$

and

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{62}$$

$$\bar{y} = \frac{1}{N} \sum_{i=1}^{N} y_i \tag{63}$$

of$\hat{r}_p = 0.93$ between the two series! When it is 1, this is a perfect correlation, 0 no correlation, and -1 an anti-correlation. The factor Fcovid is therefore very strongly correlated with the number of deaths from COVID-19 per 100,000 inhabitants, whatever the country, region, city, or even a boat !!! Under these conditions, it can be expected that:

- there will be no health problem with COVID-19 in Africa and South America (only a few very dense cities slightly affected) because the population is young and the population density overall low.

- the epidemic risk in India is higher than in Africa, because the population density is greater and less young. But it remains very moderate despite everything. The attendance of the great temples must be prohibited however !
- Europe, United States, China, Russia: the big cities are very affected because the population is rather old and the density of population strong. Wrong conjunction. It is therefore better to live in the countryside in these countries !! As such Sweden is less affected because the population density is low! This country therefore does not manage its epidemic better than the other pauses in Europe ... The risk of secondary secondary epidemics is high in these cities as long as no vaccine is found.
- For China, the risk is very serious, because the country is made up of a cluster of very dense large cities, with an overall elderly population as a result of the one-child policy. It is probably the most fragile country in the world. It is hard to imagine a Chinese plot under these conditions ...
- religious, sports or cultural gatherings are real disasters! Iran is probably the best example, because the density of population, even transient during these events largely compensates for the youth of the population! France, Italy, South Korea were all the victims of these rallies! They should be banned until a vaccine is found. It was the youth of the Iranian population that saved it in terms of the number of deaths.
- Finally, the singularity of COVID-19 is the increasing aggressiveness of the virus with age! Understanding this mechanism will be key to treating the disease.

In conclusion, the epidemic is not going to have a significant impact in most countries of the world, and especially in Africa as the WHO has expressed concern. It is a problem of big cities with old populations. Moreover, gatherings, such as cruises are to be avoided as long as there is no vaccine. Airplane flights are also a problem, due to the temporary high concentration of the population. Until a vaccine is found, all countries currently concerned will remain very fragile.

4.4.2 Exact estimate

There are many quantities to quantify the risk associated to an outbreak: the risk of being contaminated, the risk of being very sick, the risk to be in intensive care units and the risk of death. It can be defined per any object, the object being a people, a boat, a meeting, a city, an area or a country.

If dN/da is the elementary number of people per age group in a country of N_{tot} people,

$$\int_0^{a_{max}} \frac{dN}{da} da = N_{tot} \tag{64}$$

or

$$\int_0^{a_{max}} f_p(a)\, da = 1 \tag{65}$$

where

$$f_p(a) = \frac{1}{N_{tot}} \frac{dN}{da} \tag{66}$$

is the normalized age structure.

For a given age group, the risk of deaths is

$$r_d(a) = f_p(a)\, f_d(a) \tag{67}$$

where $f_d(a)$ is the absolute fraction of contaminated people who will die from the COVID-19, since fatality is strongly age-dependent. Here, $f_d(a)$ is given by the relative distribution of deaths [6], normalized to the mean value of the estimated fatality rate δ_d, i.e.

$$\int_0^{a_{max}} f_d(a)\, da = \delta_d \tag{68}$$

Regarding the studies performed recently, $\delta_d = 0.7\,\%$ deduced from the Diamond-Princess cruise liner case is a robuste reference.

Therefore for a whole country, knowing the age structure, the total risk of deaths is the integral over the ages,

$$r_d = \int_0^{a_{max}} f_p(a)\, f_d(a)\, da \tag{69}$$

and this parameter alows to compare the risk of oubreak between different countries or world areas, which have different age structures. It is therefore straightforward to estimate that the risk is small in Africa, since most of the population is young, and much more critical in Europe.

It is well known that population density is a major factor in the development of an outbreak, since in high density areas, the risk of interaction between people, and so for contamination. This is the reason why cities with high population densities are the main foci of the outbreak.

With similarities with cross-section theory, the probability of interaction for a test person is the product of the local population density n times the effective surface σ of this person (cross-section). This number may be also a function of the age, if some societal distanciation may take place naturally (old persons are living close or far from the rest of the family)

$$p_c(a) = \sigma(a)\, n \tag{70}$$

Therefore,

$$f_p(a)\, f_d(a)\, p_c(a) = f_p(a)\, f_d(a)\, \sigma(a)\, n \tag{71}$$

and integrating over the age, the local risk of deaths is

$$r_d^{loc} = n \int_0^{a_{max}} f_p(a)\, f_d(a)\, \sigma(a)\, da \tag{72}$$

For a city like Paris, with $n = 20000/km^2 = 0.02/m^2$, the mean surface per people is $S = 1/n = 50\, m^2$[2]. Even if the density is high, the mean surface is much larger than the surface of interaction corresponding to the vertical projection of the body of a person, which can be estimated to $s = 0.78\, m^2$. Therefore, only binary interaction must be considered.

Ultimately, the number of deaths for a given city is

$$N_d^{loc} = N_{loc} r_d^{loc} \tag{73}$$

or for Paris, with $N_{loc} \simeq 2.2 \times 10^{+6}$ inhabitants, and neglecting age structure $N_d^{loc} = N_{loc} \delta_d s n \simeq 240$. It is below the absolute osbervation which is about 1450 the 27th of April 2020, which allows to estimate the effective surface of interaction in the ratio $1450/240 = 6$. Considering that the surface of interaction in the lockdown is $\sigma_{lockdown} = 4.5\, m^2$, the number of deaths at Lyon and Marseille should be only 140 and 87 respectively, which is close to observations at the save date, since their density and populations are $\left(0.01/m^2, 0.0035/m^2\right)$ and $\left(0.44 \times 10^{+6}, 0.8 \times 10^{+6}\right)$. At Wuhan, with is population of $N_{loc} \simeq 11 \times 10^{+6}$ and a density of $n = 0.00582/m^2$, the total estimated number of deaths is 2000 very close to the observed value around 2570.

Without lockdown, the surface of interaction is much larger. If the total number of people that can be contaminated is about 60 % of the population before the natural end of the outbreak thanks to a value of $R_0 \simeq 3$ for the COVID-19, the number of deaths should be 9240. So surface of interaction is $\sigma_{free} = 9240 \times \sigma_{lockdown}/1450 = 28\, m^2$, about half the mean surface in Paris. The estimated $R_0 = \tau_i \sigma_{free}/S = 3.6$ and in the lowkdown phase $R_0 = \tau_i \sigma_{lockdown}/S = 0.57$ close to the observations. The fact that the estimated R_0 values match those of France suggested that the effective surface of interaction of people is almost universal, in the lockdown or free phases.

Concerning a differential distanciation, it can be modeled according to the law

$$\sigma(a) = \sigma \tag{74}$$

for $a < a_{ref}$,and where $\sigma_{lockdown} < \sigma < \sigma_{free}$ depending upon the strength of the lockdown, and $\sigma(a) = \sigma_{lockdown}$ for $a > a_{ref}$. There are some arbitrariness in the determination of a_{ref}, but it could be place after 75 years old.

[2]The mean distance is $\sqrt{S}$ and for Paris, it is about $7\, m$

5 Western African Ebola virus epidemic (2014-2015)

In March 2014, a major outbreak of the virus Ebola started in Guinea and spread rapidly in neighboring countries like Liberia and Sierra Leone. It is a viral haemorrhagic fever of humans, with a very high fatality rate, around $\delta_d = 50\,\%$, about hundred time what is estimated for the virus SARS-cov-2. The dynamics of the outbreak is different from COVID-19, since mean incubation time is about $\tau_i = 10$ days (ranging between 2 and 20 days), while itis $\tau_i = 4$ days approximately. The main difference is that durong the incubation period, sick people may contaminate other people for the SARS-cov-2 virus, while in principle, the contamination is only possible if first symptoms appear. Furthermore, a very close physical contact is necessary for a contamination by the Ebola virus, while, oral transmission is likely the main process for the SARS-cov-2.

The example of Liberia is considered, since the number of cases is rather large, making statistics quite accurate. This example allows to investigate the capability of the model to describe this type of outbreak, and if from data, standard R_0 can be retrieved. In addition, it is important to test the case where likely the number of tested cases if well known, since all sick people are rapidly well diagnosed, and the chain of contamination may be rather well known.

As shown in Fig. 102, the whole outbreak can be well reproduced by the model, despite its simplicity. As for the SARS-cov-2, it is a multi-steps outbreak, as observed in many countries, with a major propagation after day 71, while initial evolution suggested that the Ebola outbreak was totally controlled. From the early phase of the second rise and taking an averaged time of contamination of 3 days (before death in general), $R_0 \simeq 1.5$ approximately, close to the values that have been estimated. Therefore the contagiosity of Ebola virus is much less than SARS-cov-2. This is likely because the transmission of Ebola virus requires physical contacts with the sick person and possibly its infected fluids, while for SARS-cov-2, it is likely mainly aerial transmission in addition to physical one on surfaces. Consequently, only $33\,\%$ must be immunited by a vaccine, to protect the whole population from Ebola virus. Furthermore, R_0 is rather low since people that have symptoms die rapidly. So this cut quickly the probability of transmission. In that sense, even if the rate of mortality of Ebola virus is extremely high, it is less dangerous at the world scale than VIH or SARS-cov-2 viruses.

From Fig. 102, it can be shown that the cumulative number of certified cases is consistent with the deaths number, over the whole outbreak duration. The good agreement is the consequence of the process of contamination, which allows to track more easily sick people, because physical contact is necessary.

A long tail of low level daily cases and deaths is observed during several months, with some similarities with South-Korea, as shown in Fig. 103. This highlights the need of a strong control of the outbreak during many months for the COVID-19, and the need not to relax the efforts made. The occurence of the peak in the outbreak is just a step in the global management of the virus spread. Permanent control will be likely necessary, regarding the high reproduction factor R_0 of the SARS-cov-2, as compared to Ebola virus.

6 Conclusion

A simple zero-dimension model of the coronavirus outbreak has been developped, and is able to give indications on the near future if the daily trend of the cumulative number of contaminated people is confirmed. As this model is general, it has been successfuly tested against the seasonal flue, and with standard simulation parameters, the 10000 deaths per year in France is well recovered.

At the date of the 6th of March, there is no control of the outbreak in France, and all citizen will face the disease if nothing is changing in the management of the outbreak. The number of deaths will be extremely large, and the health care units totaly overloaded during several months. Such a situation is similar in Italy, and in this country the situation is worse, since the mortality rate seems to be much higher, about $4\,\%$, like in China, while it is about $1.5\,\%$ only in France. The situation is simular in Switzerland but with a much lower fatality rate. In South-Korea, though the outbreak is not totally stabilized, the evolution is favorable thanks to the quarantine, and it should stop after 120 days from the model. In Iran, the outbreak is not yet stabilized, but the authorities have clearly acted, but very late as compared to other

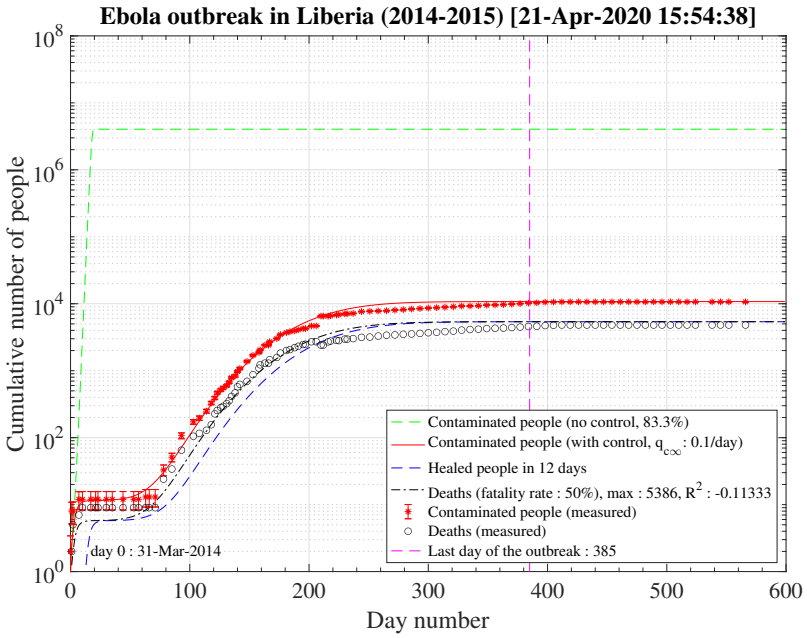

Figure 102: Cumulative number of contaminated people and deaths by the Ebola virus outbreak in Liberia (West Africa, 2014-2015).

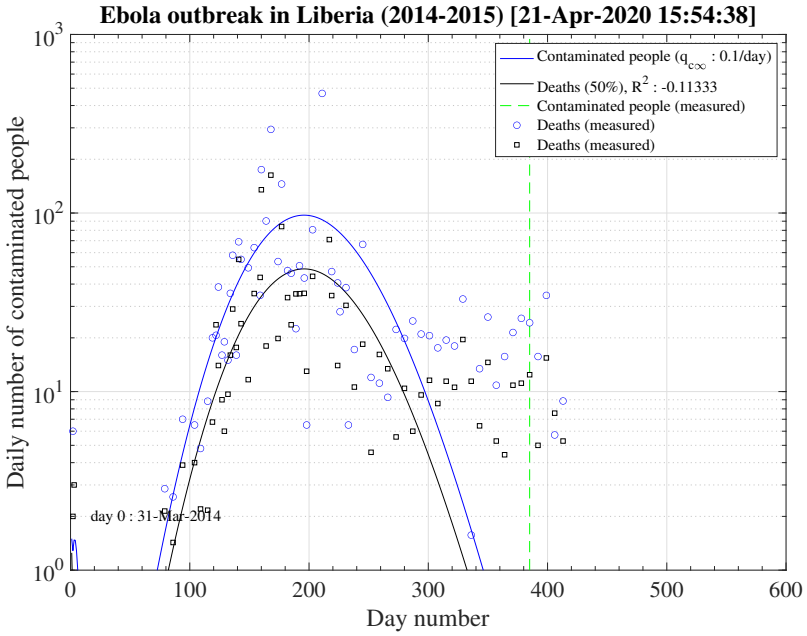

Figure 103: Daily number of contaminated people and deaths by the Ebola virus outbreak in Liberia (West Africa, 2014-2015).

countries, leading to a very large number of ill people, and deaths. The outbreak in Spain and USA are very similar in their respective time evolutions.

In China, where the model have been successfully applied too, the residual rate of contamination has been drastically lowered to $q_{c\infty} = 0.001$ by a severe quarantine like in Wuhan city and around in Hubei state, but also elsewhere, each time the virus was emerging suddenly [2]. This approach was successful, and from predictions, the outbreak will end in March 2020.

South Korea, faced two phases of the outbreak, and a third one is starting the 18th of March. The second phase of the outbreak whose origin is well identified (large religious meeting), highlights the risk of a restart of the outbreak everywhere it has be stabilized, since most of the population is not immunited against the virus, by the artificial control of the outbreak. Only a massive vaccination campaign may reduce definitively the risk of a periodic restart of the outbreak as it was indicated and observed in South Korea. China is clearly aware of this situation, and the number of certified cases is stable, above expectations, because of external contaminated people entering the country

From the analysis of the eight most concerned countries, some conclusions can be drawn with quantitative numbers. There are two ways to control the disease: (i) without any vaccine available, only a drastic quarantine could reduce the daily contamination rate. This option seems not considered yet (11th of March) by the French governement while Italian one decided it the 8th of March for about one month, regarding the overload of the hospitals. In Italy, the effect of the quarantine are not visible the 11th of March, but a good probability of success like in China will require a strict application of the quarantine. This option is the worse for the economy. (ii) an efficient vaccine is found, and in few weeks, the outbreak is stopped. Unprobable regarding usual time it takes to develop such a medication (about a year).

So, without strong quarantine to reduce drastically the contamination rate q_c, a dramatic situation will likely occur in France very soon, and the example of what append in Italy gives clearly indication on what should be done quickly. Nevertheless, the situation between the two countries seems to be different concerning the number of deaths, since it is significantly higher in Italy than in France.

The fatality rate is subject to different values from countries to countries, with similar health care systems. This may result from the level of activity of old people within the society. The virus is spreading actively, concerning all classes of age, but older people are much more sensitive to severe form of the disease. The elderly must be isolated from young children to reduce the risk of contamination.

Based on the modeling of the outbreak in the line cruiser Diamond Princess, a low fatality rate is estimated, about 1.0 %, close to South-Korea. In this case, the number of contaminated people is know exactly. The surprizing low fatality rate despite of the old mean age of the passengers, may indicate that the co-morbidity is the key aspect of the age dependence of the fatality rate that has been estimated in China. If the number of deaths is the reference to estimate the outbreak time evolution, the number of contaminated people is strongly underestimated, as this number is growing. Nevertheless, the time evolution of the number of people requiring respiratory support in continuous health care units is not well reproduced. At the time of the 13th of March, it is not possible to decide if this low fatality rate scenario is effectively realistic.

If the coronavirus is seasonal like the flue, this would be an extraordinary chance. In that case, the outbreak will stop naturally quite quickly. Nothing tends to prove this fact at present time, since it develops in countries with have hot and cold weather too. The evolution of the virus in Africa will be very interesting from this point of view.

It is important to notice from WHO data, that the outbreak has almost always a quiescent phase of several days (or weeks) because the virus is first imported by travellers using fast and long distance transportation systems that are efficiently detected at the airport principaly (Levy flight effect). Once the outbreak becomes domestic, the local growth of the number of contaminated people becomes rapidly dramatically high.

Most of the people believe that the coronavirus is a marginal problem, as compared to the annual flu, or even the Spanish flu in 1918. When calculations are performed from the model with values successfully compared to observations, it is possible to see that the coronavirus is a very serious health problem at the world scale. It should be recalled that the Spanish flu in 1918 killed $N_d = 218000$ persons in France. At that time, $N_{tot} = 38.67 \times 10^6$, so the ratio $N_d^{flu}/N_{tot} = 0.56\,\%$ (to the whole population), while for the coronavirus, it may reached

$N_d^{coronavirus}/N_{tot} = 1 - 1.5\,\%$, so twice or three times more if the outbreak is uncontrolled. The new coronavirus outbreak is therefore a major event, and not a small problem, and could be worse than the Spanish flu, which killed between 50 and 60 millions of people over the world. This is particularly critiacal if mortility rates in China and Italy are considered and widespread. The initial reproducton factor R_0 of the coronavirus outbreak is estimated to 5 apprimately, twice more than the Spanish flue [7].

Finally, there is an important difference between the Spanish flue and the coronavirus outbreak until no vaccine have been found for the later. Indeed, for the Spanish flu, the disease has disappeared naturally, because the aggressivity of the virus has progressively decreased during the outbreak, a well known behaviour, and because the probability of contamination p_c has also decreased substantially since many people have been contaminated (immunity) or died. For the coronavirus, p_c is still close to unity at the time the report is written, which mean that the reservoir of people that can be still contaminated is very high. So the outbreak may restart very quickly is no active and permanent watch is not achieved everywhere in the world. An example is the Ebola virus, which periodically appears in Africa, and remain very contagious. Therefore, the success in controlling the coronavirus outbreak in China does not mean that the whole effort is achieved, and the standard life can restart as usual. Considerable care should be taken in all the countries. The two phases of the outbreak in South-Korea are a good example of the fragility of the situation, once the outbreak is ended by quarantine.

Ultimately, the case where the coronavirus outbreak would have been like the seasonal flu, with a fatality rate of 0.1 %, has been considered. In this case the number of officialy contaminated people is totally underestimated, it is possible to reproduce it for France, day zero being the 10th of February. The contamination rate should be very high and constant $q_{c0} = q_{c\infty} = 0.4$, and the number of people requiring an active ventilation in continuous health care units must exceeds the number of available respirators by mid of March. The hypothetic number of contaminated people is about 65000 at the date of the 11th of March. All the population should be immunited by end of March, and 47000 people should die from the outbreak, that's much higher than the seasonal flu, because of the much higher contamination rate to reproduce the daily increase of deaths. Coming two weeks should be crucial to conclude about the two scenarii at the date of the 13th of March.

The study of the Ebola outbreak in West Africa during 2014-2015 shows the ability of the model. It gives a rather good estimate of the reporduction factor $R_0 = 1.5$, and with a constant fatality rate, the cumulative number of certified cases and deaths may be well reproduced. A tail of daily cases and deaths before the full end of the outbreak is observed, which clearly indicates the need to maintain strict survey during many months after the peak to avoid a possible restart of the outbreak.

7 Interesting links

A very interesting and well documented french article on the Covid-19 outbreak. One of the best document on the COVID-19 ever seen can be obtained here. Another intersting link of a standard SIR modeling, which gives indication how to fight COVID-19.

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Appendix A

Automatic database access script

Appendix B

Main script