Title: Chaos theory applied to the outbreak of Covid-19: an ancillary approach to decision-making in pandemic context

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Abstract: Predicting the course of an epidemic is difficult, predicting the course of a pandemic from an emerging virus even more so. The validity of most predictive models relies on numerous parameters, involving biological and social characteristics often unknown or highly uncertain. COVID-19 pandemic brings additional factors such as population density and movements, behaviours, quality of the health system. Data from the COVID-19 epidemics in China, Japan and South Korea were used to build up data-driven deterministic models. Epidemics occurring in selected European countries rapidly evolved to overtake most Chinese provinces, to overtake South Korean model for France and even Hubei in the case of Italy and Spain. This approach was applied to other European countries and provides relevant information to inform disease control decision-making.

Introduction

The new coronavirus SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) is responsible for the Covid-19 epidemic that broke out in Wuhan (China) on December 2019 [1]. Although being identified in the early stages of the epidemic as being close to two other coronaviruses (SARS and MERS) [2], its epidemiological risks in terms of propagation and lethality were not known. Investigations reported by the Chinese Centre for Disease Control and Prevention (China CDC) demonstrated that a new coronavirus, now known as SARS-Cov-2, was at the origin of this epidemic [3]. The retrospective analysis of the earlier transmission in Wuhan revealed that human-to-human transmission had occurred since the middle of December through close contacts [4]. After a very rapid dissemination in the Hubei province, the disease has spread to all the other provinces in China. Currently, the epidemic seems to be getting under control thanks to strict control measures [5]. During its early spread in China, the virus also reached several countries in the world, in particular Japan where early measures enabled to control its spread relatively well [6], although restarts cannot be excluded. More recently several important new clusters broke out in South Korea, Iran and Italy by the end of February. Beginning of March most of Europe was affected, to be followed by the USA. Currently the epidemic is affecting the whole world [7].

Various techniques have been developed to model the epidemics of infectious diseases. Most of these are based on compartment models which separate the populations in main classes. The model enables to represent the interactions between these classes based on pre-established mathematical rules. The simplest formulation comes from the early work by Kermack and McKendrick in the 1920s [8] and involves three classes: one for the people sensitive to the disease who are prone to contracting the disease, a second one for the infectious people who have contracted the disease and can infect susceptible people, and a third one for the people outside this cycle either because they became immunized after recovering, or because they left the study area, or finally because they have died.

Although some specific model formulations can be usefully fostered, all the mechanisms may not always be known and therefore the complete formulation of the equations governing an epidemic will generally be unknown. This is especially true when coping with a new disease outbreak. Three main problems will be met in a modelling perspective of such a situation: (1) What are the relevant variables for a given epidemic? (2) What are the governing equations coupling these variables? (3) What are the parameter values of these equations? And, in between these questions, two other very practical questions: (4) what observations do we have to build and constrain a model? And, as a corollary, (5) how to reformulate the governing equations based on the observations we have?

Based on the chaos theory [9], the global modelling technique [10-13] offers an interesting alternative with respect to other approaches. It is well adapted to the modelling and study of unstable dynamical behaviours: it enables to detect and extract the deterministic component underlying the dynamical behaviour; and, as a consequence, it can be a powerful approach to analyse dynamics which are highly sensitive to the earlier conditions and to detect chaos (see Suppl. Mat. 1). Another interesting aspect of this technique comes from the potential it offers to work even when important variables are missing which is generally the case in epidemiology. Finally, it has proven to be a powerful tool to detect couplings between observed variables, and even, when all the dynamical variables are observed, to retrieve the original algebraic formulation of the governing equations in a compact and potentially interpretable form[14].

Numerous studies have been based on chaos theory to study epidemiological behaviours [15-17] but a global modelling approach *per se* has rarely been applied to biological systems. The first replicable application was in ecology [18]. In epidemiology, it enabled to obtain an interpretable model for the epidemic of Bombay bubonic plague (1896-1911) by extracting the couplings between the human epidemic and the epizootics of two species of rats. Although obtained from observational time series without strong *a priori* model structure, it was found possible in the latter case to give an interpretation to all the model's terms [19]. A model was also obtained for the West Africa epidemic of Ebola Virus Disease (2013-2016) coupling the two observed variables made available with a regular sampling: the cumulated number of infected cases and deaths [20]. In the present study, this modelling approach is used to model the current Covid-19 epidemic in Asia (China, Japan and South Korea) and then to produce scenarios for fourteen other countries where the disease was introduced later and spread locally.

Two main data sets were used for the present study. The official data from the National Health Commission of the People's Republic of China [21] were used to study the original outbreak at China's scale (from 21 January to 20 March 2020). The data from the Johns Hudson University [22] were used to monitor the outbreaks at the province's scale in China and at the country's scale for other countries. Three original time series were considered: (1) the daily cumulated number $C_\Sigma(t)$ of confirmed cases, (2) the daily current number $s(t)$ of severe cases and (3) the daily cumulated number $D_\Sigma(t)$ of deaths; from which derivatives (required for the modelling approach used in the present study) were deduced, hereafter noted $C_1(t)$, $s_1(t)$ and $D_1(t)$, respectively. Details about all the pre-processing are provided in Suppl. Mat. 2 (Fig. S1).

Applied to a set of three time series derived from the original observations – $C_1(t)$, $s_1(t)$, and $D_1(t)$ – several models were obtained [23] for the period starting from 21 January to 5 February

2020, four of them leading to chaotic behaviour (one of these four, model **M**, will be taken as an example), and another one converging to a fixed point. The five models were built on a common algebraic structure. Model **M**

$$\begin{cases} \dot{C}_1 = -0.10530723\, D_1^2 + 2.343\times10^{-5}\, C_1^2 + 0.15204\, s_1 \left(D_1 - 0.01451520\, C_1\right) \\ \dot{s}_1 = -0.20517824\, C_1 + 0.44040714\, s_1 + 0.16060376\, D_1^2 \\ \dot{D}_1 = -0.00011493\, C_1\, D_1 - 1.215\times10^{-5}\, C_1\, s_1 + 0.2844499\, D_1 + 2.38\times10^{-6}\, C_1^2 \end{cases} \quad (1)$$

comprises eleven terms. It suggests the existence of strong but complex nonlinear couplings between the three observed variables. Unfortunately, the analytic formulation appears too complicated to be interpreted. This high complexity shows that these three variables together are not the variables originally at work in the processes: the present model is a reformulation (and probably also a rough reduction) of the original processes.

The numerical integration of the model shows that, after a relatively short transient of approximately 15 days, the model trajectory can reach a steady regime laying on a chaotic attractor. Three projections of the phase space are shown in Figure one illustrating that, after convergence, the trajectory will stay in the ranges [+2100; +8000] for the daily number of newly confirmed cases, [–100; +1200] for daily variations of severe cases number and [+30; +100] for daily deaths. Three simulations have been performed from different initial conditions. These small differences generate different trajectories that will all converge to the same chaotic attractor, simultaneously illustrating, the high sensitivity to the initial conditions and the consistency of the dynamical behaviour. A more detailed analysis of the model (see Suppl. Mat. 3 and Fig. S2) proved that the present dynamic is very close to a phase non-coherent regime, that is, a much less predictable behaviour. The trajectory reconstructed from the observational data (thick black line) shows the relatively good consistency of the model with the observed data (which may undergo various perturbations, which are smoothed by the model). Note that only the earlier part of the data set was used to obtain the model (the model was obtained on 6 February 2020). The outbreak was obviously still on its earlier transient at this time while no inflection had already been evoked. The data show that the inflection started on 6 February 2020, after which observations respectively stayed in the range [+1800; +3000] for $C_1(t)$, [–10; +1800] for $s_1(t)$ and [+60; +120] for $D_1(t)$. These values are not fully consistent with the model's variables ranges at convergence. This is due to the increased actions taken to control the disease, which prevented the propagation of the disease before it could reach this level. This control action was effective in slowing down the spread of the epidemic itself, but not on the fatality numbers as no treatment was available to cure the infected people. The reduction of severe cases and deaths could therefore only be caused by measures to slow down the epidemic progression. That can explain why the maximum values of daily deaths simulated by the model could not be reached by C_1 but was exceeded by s_1 and D_1.

In terms of temporal evolution, the three simulations clearly illustrate the high sensitivity to the initial conditions (Fig. 2): trajectories may alternatively come closer and move away one to another but do not converge to a single time evolution. It also shows that the large oscillations observed in $s_1(t)$ (Fig. 2b) can be reproduced by the model although they are slower in the simulations. Finally, the regular increase of the daily deaths during a transient regime is also well reproduced although the maximum number of death is in the end underestimated by the model.

At present, the epidemic seems to be getting under control in China. Three simulations were run using recent data (starting on DoY-72 7pm; DoY-73 7am and 7pm, see Figure two in dashed brown lines) showing that a quick restart must be expected if the control measures were to be released now before the epidemic is entirely wiped out (immunization is assumed to be insufficient to modify the dynamic significantly).

The same model was used to simulate the evolution observed in Italy (light coloured lines) showing a good agreement with the observational data (thick red line). This agreement may be surprising considering the difference in population size between the two countries. The behaviour observed in China relies, for more than 83.5%, on the Hubei province which population size is quite similar to that of Italy. Comparing with the evolution of the epidemic in Italy, this simulation is backing up the fact that the strict control measures applied by the Chinese authorities played an important role in the control of the epidemic. Very strict measures were taken in Hubei (total quarantine of Wuhan and of a part of Hubei province) while the number of daily new cases was around 340-600 in China. Similar measures were taken in Italy (on 8 March 2020) and more recently in Spain (14 March 2020) but comparatively much later, when the number of cases reached (around 2000 in Italy and 1500 in Spain, see Table 1). In France the recent control measures enforcing confinement of all the French population based on voluntary basis but under government control has arrived later than in China but earlier than in Italy and Spain in terms of number of cases (~1000).

Using the model, the cumulated counts $C_{\Sigma}(t)$ and $D_{\Sigma}(t)$ can also be calculated by the numerical integration of the simulations from which the model's fatality rate can be estimated (see Suppl. Mat. 4 and Fig. S3). This rate progressively converges to 1.4%. Considering the ability of the virus to propagate easily and silently in both Asia and Europe, and now everywhere else, and at all society levels, a tremendous number of people will surely be infected by the SARS-Cov-2 in the weeks and months to come, requiring specific measures to slowdown the propagation of the disease. Though, it may probably be extremely difficult to control the disease completely and resurgences must be expected [24].

It is important to note that no obvious changes did immediately appear after the authoritative lockdown of the Wuhan city on 23 January 2020 followed by the other strong lockdowns of many other prefectures on 23 and 24 (DoY 23 and 24) in the Hubei province which constitutes the main focus of the outbreak. Note that, on 23 January 2020, the official counts were close to 830 confirmed cases, 177 severe cases and 25 deaths. A clear decline could be observed after this event and 12-13 days later in the daily number of new cases when reaching a peak of almost 4000 new cases of infection per day. The peak of 100-140 daily deaths was reached after 6 to 7 days more, before a clear decline started two more weeks later.

The global modelling technique was used in its canonical form to obtain polynomial models for eight of the mostly affected provinces in China (the Hubei, Zhejiang, Henan, Anhui, Hunan, Jianxi, Guangdong and Heilongjiang) as well as for Japan and South Korea (examples of both the original and model phase portraits are shown in Fig. S4, see also Suppl. Mat. 5). The original and modelled phase portraits of these models are very consistent. These models were obtained at the end of the outbreak or at least while it had started to decrease; it is why all these models converge to fixed points: their regimes relate to dynamics that are not, --or not anymore --, chaotic. These were used to perform scenarios for the outbreaks in progress in Iran, and in Europe, even more so in Italy, France and Germany.

Simulations are provided in Figure three for fourteen countries (corresponding epidemic curves are also provided in Fig. S5). These show that Italy has now exceeded the Hubei scenario, whereas Iran is presently in between South Korea and Hubei. France and Germany have exceeded the South Korea scenario. But this does not mean that the present scenario will be kept until the end. Actually, these closest scenarios have largely and quickly evolved during the last days. Based on the bulletins[23] published online from 9 February to 15 March 2020, the progressions of these analyses are presented in Figure four. The models used to establish the scenarios are / or seem to correspond to situations under control: The number of new cases has come to zero in China on 19 March 2020, and it exhibits relatively controlled evolutions in Japan and South Korea, although progressively exceeding their own scenario. But it is not the case for the other countries under study. For most European countries, the scenarios are still quickly evolving from Heilongjiang to Hubei types of scenario, highlighting that the outbreaks are not under control in Europe and that strong measures are still not able to slow down the disease. Italy has even largely exceeded the Hubei both in terms of number of cases and deaths. At present, possibly partly due to the delay expected between the measures and their effect (at least 12 days), there is no direct correlation between the time of implementation of the most stringent control measures and the evolution of the disease situation in the different countries (in terms of number of cumulative cases and weekly cases, see Table 1). At present, there is no direct evidence neither on the impact of the type of enforcement of such measures (state control *vs* volunteering basis) on the disease evolution outcome, this will require probably more investigations including sociological analysis of the socio-cultural factors influencing control measure implementation between countries (Fig. S6). It is still too early to identify the best-case scenario but the earlier the reaction the most likely countries will remain on the path of a less dramatic scenario. However the analysis shows that in some countries such as South Korea, Norway, Sweden, Austria the detection capacity is stronger than in the others – which if maintained is likely to have an impact on the outcomes of the control measures in place (see Table 1).

Even considering the expected delays between the lockdown date and the impact on the epidemic curves (twelve days for infected cases, seventeen for the stabilization of deaths, thirty for deaths decrease) the possibility that the Italian outbreak will hugely exceed the Hubei scenario is now more than obvious and several other countries are potentially following the same path.

For Iran, despite a quick start, the data suggest a relatively high efficiency to slow down the epidemic. Unfortunately, information is too scarce to confirm this behaviour independently.

Discussion During the last two weeks, in Europe, the most relevant scenarios have quickly evolved, starting from relatively light situations to harder and harder scenarios later confirmed step by step (Fig. 4). Following this path, Italy has largely exceeded the harder situation met in the Hubei province; Spain has also reached and now exceeded this scenario several days ago. It is closely followed by Switzerland, France, the Netherlands and the United Kingdom. Iran seems to converge on a scenario in between South Korea and the Hubei province. Several other countries in Europe have already (Germany and Norway) or will probably soon take off (Belgium, Denmark, Sweden, Austria) following the South Korean scenario.

One important question that arises from the present results is the scale of applicability. Because the model here obtained at China's scale is mostly based on the Hubei contribution, it was found to be relatively well applicable to Italy. But the daily deaths toll simulated by the model being already largely exceeded – and more and more – by the Italian observations, it shows that this model may thus be characteristic of an even smaller – intra-province – scale. Indeed, most of the cases (73.7%) and deaths (79.7%) of the Hubei province actually come from the Wuhan district [24] (on 16 March 2020). As the epidemic could be circumscribed geographically by stringent – and generalized – measures in Wuhan, the models obtained here do not simply relate to the Hubei province scale, but rather to a more confined scale the measures have permitted. It is why the model obtained from the dataset at China's scale appeared somehow applicable to the earlier development of the outbreak in Italy (both Italy and Hubei have similar population sizes).

Indeed, as 61.7% of the infected cases (76.7% of the deaths) in the Hubei province came from Wuhan and its suburb (~11.081 millions of inhabitants), the model obtained from the Hubei data finally appears more representative of the suburban scale. However, its characteristics cannot exclusively rely on a geographic scale, but also on the conditions in which it was obtained with early and stringent control. Such a hard scenario did thus happen at a suburb scale under stringent control. Without such a control, the scenarios can get much worse, even at this scale. Therefore, stringent measures similar to those implemented in China but exclusively focused on specific targets may not prevent the development of Hubei scenario types elsewhere. Without control, several such scenarios can happen at intra-province scale.

The scenarios here obtained are empirical scenarios. They compare the present epidemic situation to the situations met elsewhere without accounting explicitly for the measures taken to counteract the propagation of the disease. In this sense, the forecasts provided by these scenarios can only be valid provided equivalent measures are taken. What was observed in practice for the fourteen countries of this study is a quick evolution of all the European scenarios from relatively light (Heilongjiang to Zhejiang) to moderate (South Korea scenario) and then to relatively hard (Hubei) situations and even harder. The evolution of the last days shows that several countries in Europe are on, or will soon reach the Hubei type scenario, and that several countries will potentially exceed it largely (Italy, Spain and then France, the United Kingdom and potentially others). We will thus reach a situation in Europe with hard Hubei type scenarios at country scale and potentially much beyond since in most of the cases, later and weaker measures have been taken. But this European path to come is not the worst scenario. Actually, since the models are more likely representative of the suburban scale as explained before, each country may have to experience multiple hard Wuhan scenarios inside its borders as it is already the case in Italy. The effect of the strict control measures implemented in some countries in Europe are expected to slow down the epidemic but this effect remains hard to detect. Thanks to the very last data on 25 March 2020, several models of canonical form could be also obtained for Italy (see Fig. S7 and Suppl. Mat. 6). These models enable to estimate coming decreasing stages of the epidemic in this country. It is estimated that a situation with less than 100 new cases per day could be reached by May (see Table S5). To drop down bellow this threshold will probably be very challenging. Indeed, even in South Korea, whose measures have been quicker and more effective, could not yet reach a threshold lower than 50 new cases per day. Reaching this stage, measures will then be required before getting out from confinement, carefully avoiding new clusters restarts.

The present analysis shows that the global modelling approach, possibly in conjunction with other approaches, could be useful for decision makers to monitor the efficiency of control measures. In particular, it could be used to adapt more classical modelling approaches when needed to ensure mitigation or, hopefully, eradication of the disease [5,24] (important methodological differences between the present study and more classical modelling approaches are sketched in Suppl. Mat. 7). This work could be used also to inform decision makers in countries in other parts of the world, especially in the LMICs countries, such as in Africa [25] and southeast Asia, where numbers of Covid-19 cases are still relatively low and where rapid enforcement of control measures similar to those done in the Hubei province, in South Korea and Japan should be done to prevent a catastrophic evolution of the disease.

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References:

1. **Wuhan Municipal Health and Health Commission Report** on the current pneumonia epidemic situation in our city. Wuhan Municipal Health Commission, 2019. (http://wjw.wuhan.gov.cn/front/web/showDetail/2019123108989)
2. **Ksiazek TG *et al.*** A Novel Coronavirus Associated with Severe Acute Respiratory Syndrome. *New England Journal of Medecine* 2003, **348**, 1953-1966. DOI: 10.1056/NEJMoa030781.
3. **Zhu N *et al.*** A novel coronavirus from patients with pneumonia in China, 2019. *New England Journal of Medecine* 2020, January 24 (Epub ahead of print).

4. **Li Q *et al.*** Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. *New England Journal of Medecine* 2020; published online Jan 29. DOI:10.1056/NEJMoa2001316.

5. **Anderson RM *et al.*** 2020. How will country-based mitigation measures influence the course of the COVID-19 epidemic? *The Lancet* 2020, S0140673620305675. https://doi.org/10.1016/S0140-6736(20)30567-5

6. **Kuniya T** (2020) Prediction of the Epidemic Peak of Coronavirus Disease in Japan, 2020. *Journal of Clinical Medecine* 2020, **9**(3), 789. https://doi.org/10.3390/jcm9030789

7. **WHO** https://experience.arcgis.com/experience/685d0ace521648f8a5beeeee1b9125cd)

8. **Kermack WO, McKendrick AG**, Contributions to themathematical theory of epidemics, Part i. *Proceedings of the Royal Societyof Edinburgh, Section A. Mathematics* 1927, **115**, 700-721.

9. **Letellier C**, *Chaos in Nature*, World Scientific Publishing Company, 2019. ISBN 978-981-4374-42-2.

10. **Gouesbet G, Letellier C**, Global vector-field reconstruction by using a multivariate polynomial L2 approximation on nets. *Physical Review E* 1994, **49**(6), 4955-4972.

11. **Lainscsek C, Letellier C, Schürrer C**, Ansatz library for global modeling with a structure selection, *Physical Review E* 2001, 64, 016206.

12. **Letellier C, Aguirre LA, Freitas US**, Frequently asked questions about global modeling, *Chaos* 2009, **19**, 023103.

13. **Mangiarotti S *et al.***, Polynomial search and global modeling: Two algorithms for modeling chaos, *Physical Review E* 2012, **86**, 046205.

14. **Mangiarotti S, Huc M**, Can the original equations of a dynamical system be retrieved from observational time series? *Chaos* 2019, **29**, 023133. doi:10.1063/1.5081448.

15. **May RM**, Simple mathematical models with very complicated dynamics, *Nature* 1976, **261** (5560), 459-467.

16. **Viboud C *et al.***. Prediction of the Spread of Influenza Epidemics by the Method of Analogues. *Americal Journal of Epidemiology* 2003, **158**(10), 996-1006.

17. **Cazagrandi R *et al.***, The SIRC model and influenza A., *Mathematical Biosciences* 2006, 200(2): 152-169.

18. **Maquet J, Letellier C, Aguirre LA**, Global models from the Canadian Lynx cycles as a first evidence for chaos in real ecosystems, *Journal of Mathematical Biology* 2007, **55** (1), 21-39.

19. **Mangiarotti S**, Low dimensional chaotic models for the plague epidemic in Bombay (1896–1911), *Chaos, Solitons & Fractals* 2015, **81**, 184-196.

20. **Mangiarotti S, Peyre M, Huc M**, A chaotic model for the epidemic of Ebola virus disease in West Africa (2013–2016). *Chaos* 2016, **26**, 113112. https://doi.org/10.1063/1.4967730

21. **National Health Commission of the People's Republic of China** (2020). http://www.nhc.gov.cn/yjb/pzhgli/new_list.shtml (Last assessed on 21 March 2020)

22. **Johns Hudson University** (JHU 2020). https://github.com/CSSEGISandData/COVID-19/tree/master/csse_covid_19_data (last assessed on 21 March 2020)

23. **Bulletins GPoM-epidemiologic**, https://labo.obs-mip.fr/multitemp/bulletin-gpom-epidemiologic/ (last assessed on 22 March 2020).

24. **Ferguson *et al.*** (2020). Impact of non-pharmaceutical interventions (NPIs) to reduce COVID19 mortality and healthcare demand. DOI: https://doi.org/10.25561/77482

25. **Gilbert M *et al.***, Preparedness and vulnerability of African countries against importations of COVID-19: a modelling study. *The Lancet* 2020, **395**, 871-877. https://doi.org/10.1016/S0140-6736(20)30411-6.

List of Supplementary Materials:

Supplementary Material 1-Material and Methods

Supplementary Material 2-Data correction for country inter-comparison

Supplementary Material 3-Dynamical regime

Supplementary Material 4-Case fatality rate

Supplementary Material 5-Canonical models

Supplementary Material 6-Italy Covid-19 model

Supplementary Material 7-Comparative analysis

Figs. S1-S7

Tables. S1-S5

Fig. 1. Original and modelled phase portraits

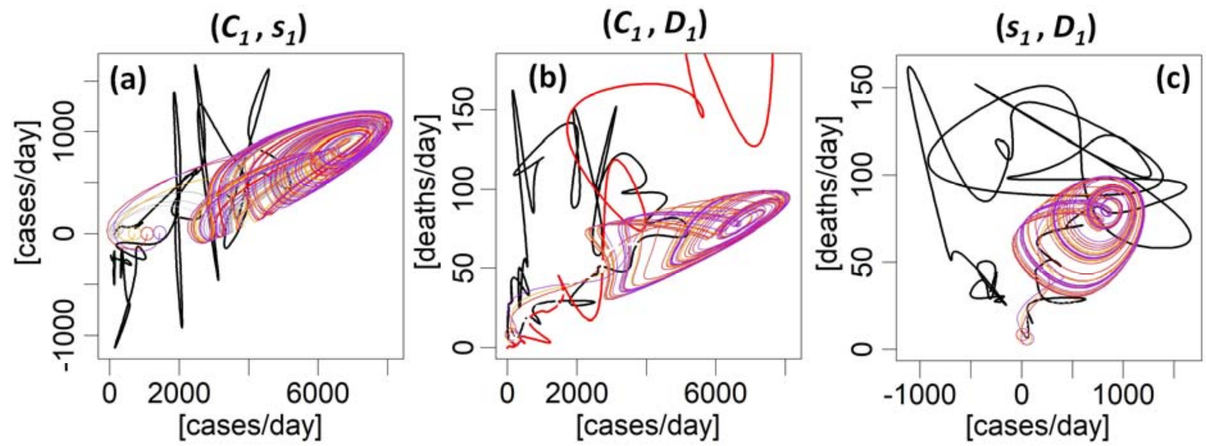

Figure 1: Three projections (C_1, s_1) in (a), (C_1, D_1) in (b) and (s_1, D_1) in (c) of the phase space as reconstructed from the model's trajectory (colour trajectories). The three colours correspond to different initial conditions (colour circles), each taken from the original data set, on 21 January 7:00 (red), 19:00 (orange) and 22 January 7:00 (purple) 2020. After a 15-day transient, the trajectories converge to a chaotic attractor. Trajectories reconstructed from the observational data are also presented: for all China (in black) and for Italy (in red).

Fig. 2. Observed and modeled time series

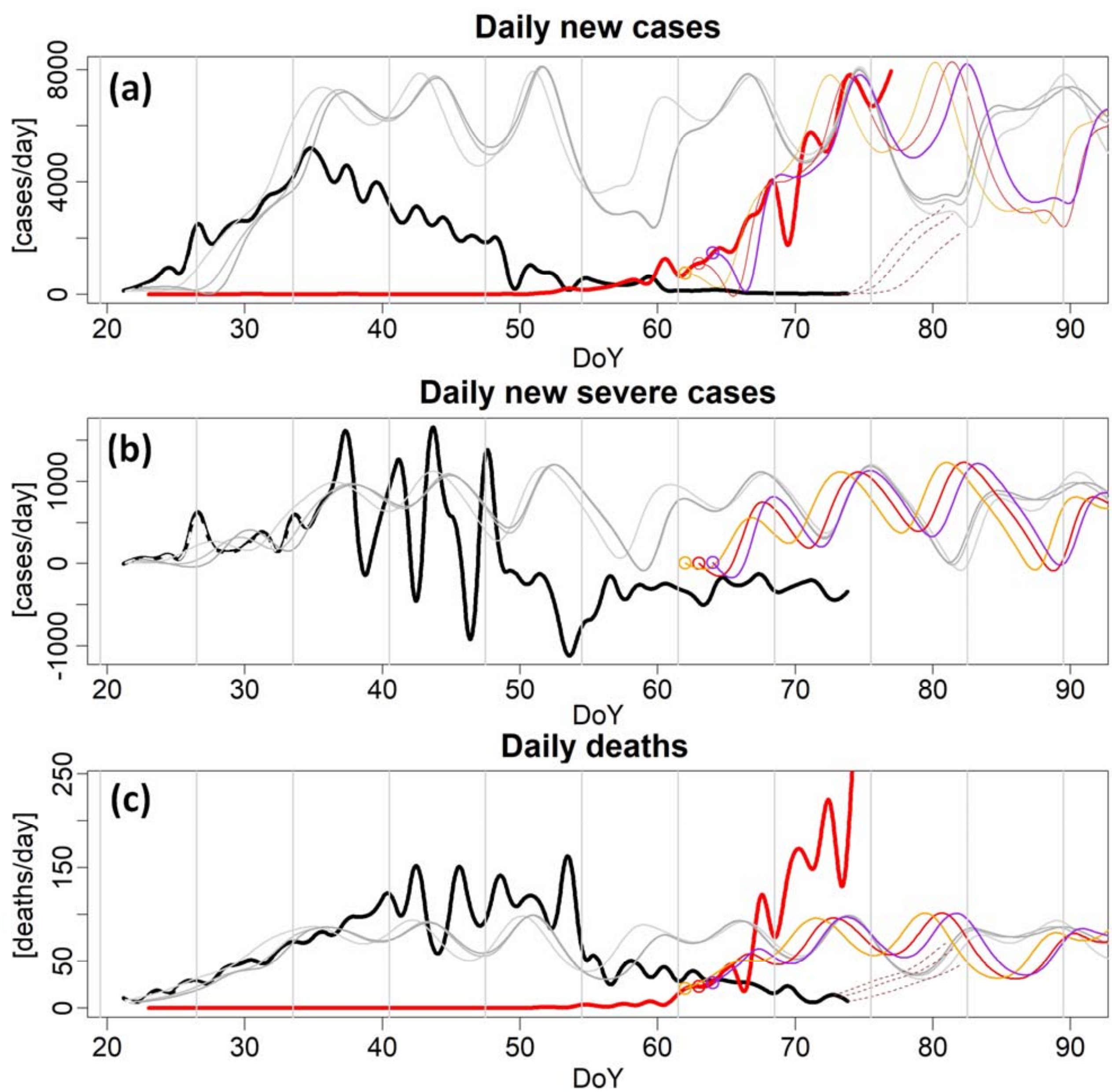

Figure 2: Observed (thick lines) and modelled (light lines) time series for China (black, gray and brown) and Italy (red, orange and purple) due to Covid-19 from 21 January (DoY 21) to 2 April 2020 (DoY 92). Three variables are presented: the daily number of confirmed new cases (a), and of severe cases variations (b) and the daily deaths (c). Note that a correction factor has been applied to the number of confirmed new cases in Italy to make the comparison with China possible (see Suppl. Mat. 2). Dashed brown lines correspond to simulations of a possible restart in China.

Fig. 3. Empirical scenarios simulations (variable C_Σ)

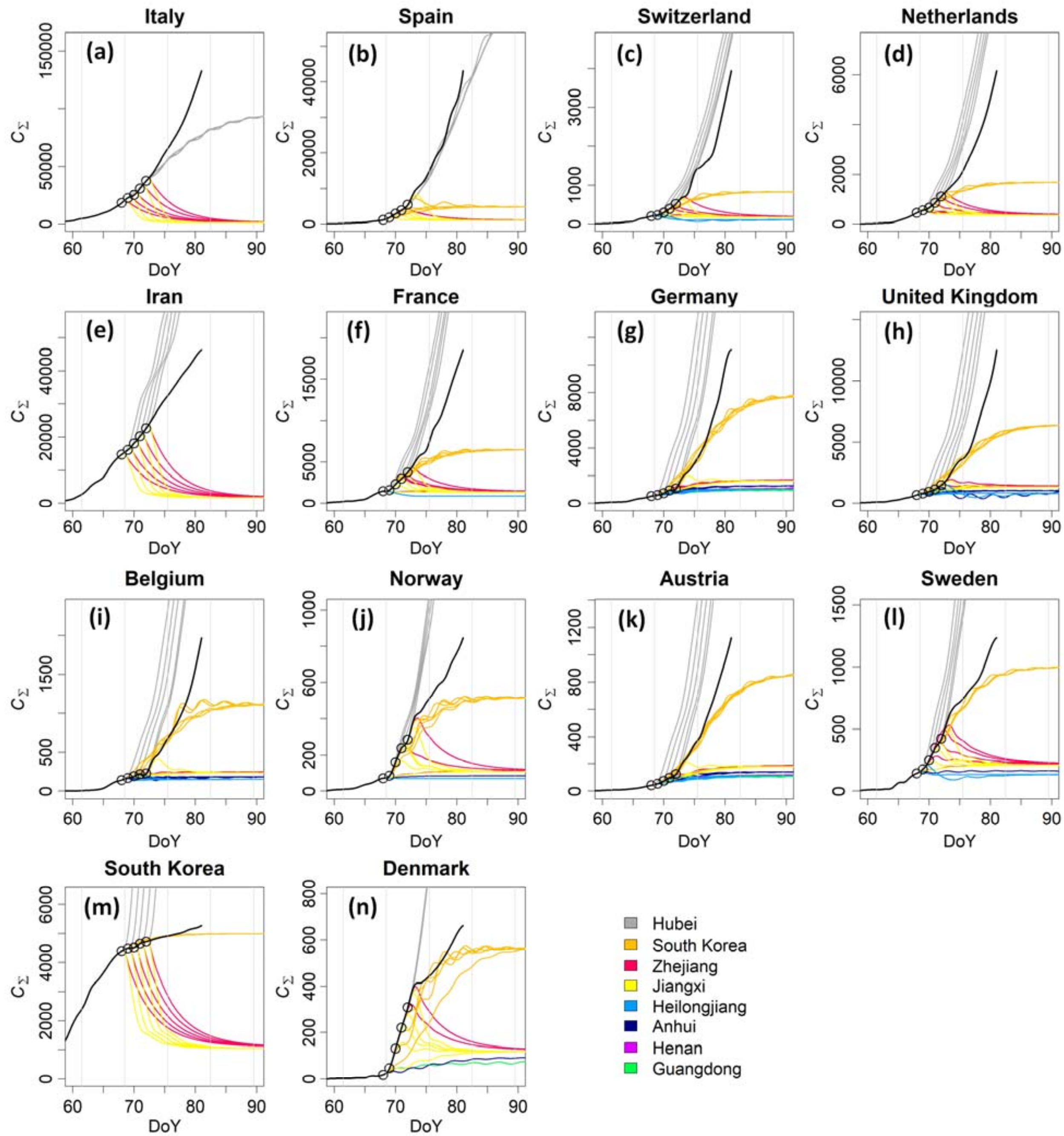

Figure 3: Empirical scenarios applied to fourteen countries based on the models obtained for seven Chinese provinces and for South Korea. For each model, an ensemble of five simulations was run starting from the observational initial conditions (black circle) 7 March (DoY 69) to 11 March 2020 (DoY 72). Population size is taken into account but age distribution is not. Correction factors were applied to each country to account for discrepancies found in comparison to the Chinese data set (see Suppl. Mat. 2). Observations are in black.

Fig. 4. Closest scenarios

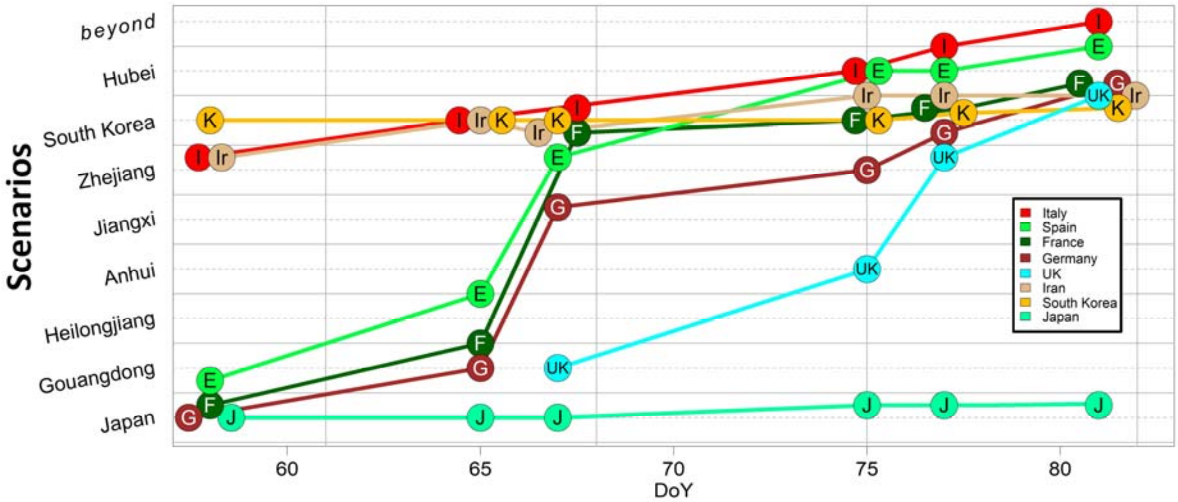

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Figure 4: Closest scenarios as a function of time for eight countries: South Korea (K), Italy (I), Iran (Ir), Spain (E), France (F), Germany (G), Japan (J) and United Kingdom (UK). Results show that the situations can evolve very quickly for the countries who did not take stringent measures to wipe out the epidemic.

Table 1. Control measures and epidemic situation

Region	Country	Control measures	Date	Cumulative confirmed cases	Cumulative corrected cases	7-day window new cases	Cumulated deaths	7-day window deaths
East Asia	**China**	Partial Lockdown (Wuhan and a part of Hubei)	23/01	830	830	-	25	-
		Nationwide lockdown*	29/01	7711	7711	7140	170	153
	Japan	Partial national lockdown (Schools and University)	27/02	214	449	252	4	3
		Frontiers closed (China then EU)	05/03 and 16/03	360 and 825	756 and 1732	307 and 659	6 and 27	2 and 17
	South Korea	Nationwide lockdown + massive testing and positive case tracing	29/02	3150	1890	1630	16	14
Europe	**Norway**	Nationwide lockdown	12/03	702	281	246	0	0
	Sweden	Social isolation of cases and ban of mass gathering	16/03	1103	772	599	6	6
	Austria	Nationwide lockdown	16/03	1018	407	355	3	3
	Denmark	Travel restrictions	14/03	827	413	402	1	1
		Partial national lockdown (Schools and University)	16/03	914	457	412	3	3
		Nationwide lockdown	18/03	1057	529	308	4	4
	Belgium	Nationwide lockdown	18/03	1486	1040	820	14	11
	Switzerland	Nationwide lockdown	16/03	2450	1470	1246	14	12
	Netherlands	Nationwide lockdown	16/03	1413	2402	1856	24	21
	Germany	Nationwide lockdown	16/03	7272	3636	3048	17	15
	France	Partial national lockdown (Schools and University)	16/03	6633	8623	7051	148	129

		Nationwide lockdown	17/03	7652	9948	7628	175	115
	Spain	Nationwide lockdown	14/03		10865	10015	195	185
	UK	Social distancing and working from home	16/03	1543	3857	3055	55	51
		Partial national lockdown (Schools and University)	23/03	5683	14208	9695	281	260
	Italy	Partial lockdown (in affected province)	23/02	155	384	377	3	3
		North country lockdown	04/03	3089	7661	6537	107	95
		Nationwide lockdown	08/03	7375	18290	14089	366	332
Middle East	**Iran**	Partial lockdown (some provinces)	19/03	18407	41416	18747	1284	855

Table 1: Control measures by country, and corresponding dates and epidemic situation in terms of cases and deaths (corrections for country inter-comparisons have been applied, see Suppl. Mat. Data 2).