FINAL REPORT PROGRAM LEFE

Program LEFE/ MANU	EQUations IDentifiées par approche hYbride (EQUIDY)	Years 2020-2023
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Context *The equations of the dynamics of interdisciplinary environmental problems are often poorly known. Thanks to chaos modeling, interpretable equations can be reconstructed directly from observations. However, such tools need to be redesigned to make them more powerful.*

Objectives *The aim of this project was to explore a new approach to detecting causal links to select variables to use for modeling; And then to develop more robust tools for extracting dynamic equations directly from the selected environmental time series. Obtaining such equations being unsure, several problems were considered. In practice for domains were considered: soil eco-hydrology, hydrogeology, epidemiology, cave atmosphere.*

Main results *The project was to start in January 2020 with the development of new tools as the first objective. Several realms were to be explored* [1-5]*, including two epidemiologic datasets (plague and avian flu). The arrival of the Sars-Cov2 virus decided otherwise.* **(I.)** *Having started monitoring the COVID-19 epidemic from the first datasets distributed by the province of Wuhan, we were able to obtain a set of dynamic equations for the epidemic of COVID-19 in China on February 5, 2000* [15]*. Since then, we started to carry out forecasts and epidemiological bulletins (in collaboration with the* ***ASTRE*** *laboratory)* [15]*. The pandemic occupied us entirely from the start until a first publication in May 2000* [5] *with a news published by* ***CNRS*** *in French and by* ***news Cirad*** *in English* [13-14]. **(II.)** We came back to this theme a year later (with N. Thenon 2021 M2 internship) then focusing on Africa where COVID-19 had been relatively little explored compared to other continents. The period also turned out to be extremely busy. A second paper was published in 2022 highlighting three important results [2]: (1) the dominant effect of the age pyramid on the epidemic amplitude and – at the same time – a very marked underestimation due to the lack of monitoring; (2) The possibility of encountering very different epidemic levels in strictly identical health and social conditions; (3) The new development of an approach aimed at estimating the effect of epidemic control policies, and its application to 17 African countries. A news was published by **The Conversation** and by **Univadis** [6-7]. **(III.)** In parallel with this work, causal wavelets were developed and tested on a set of theoretical cases presenting different types of coupling (in collaboration with the Auch branch of **CESBIO**). The approach turned out to be very effective on non-noisy cases. Investigations are now underway in the context of dynamic noise and a publication is currently being written. Several other themes were studied in parallel with these new developments. **(IV.)** In soil eco-hydrology, within the framework of **LMI-LUSES** and in collaboration with the **iEES-Paris** and the **SFRI** of Hanoi, equations extracted from a set of observations with GPoM made it possible to obtain models of earthworm dynamics, soil moisture dynamics, and for their coupling as well. Chaotic attractor solutions of these models could be obtained in each of the three cases. The coupled model made it possible to highlight a completely unexpected non-trivial coupling between earthworm activity and soil humidity. These results were the subject of a publication [3], two communications (in **IRD'mag** and **Courier de la Nature**, [8-10]), and a conference proceeding. **(V.)** In hydrogeology, equation extraction was applied to the detection of geographical couplings within a piezometric network, in collaboration with the **HUMG** of Hanoi and the **LMI-ACROSS**. The approach made it possible to detect a complex coupling between two piezometers intended to be compared to another analysis based on causal wavelet (still in progress). **(VI.)** Finally, in collaboration with the **Univ. of Valencia**, the equation extraction was also applied to the cycles of CO_2 and ^{222}Rn concentrations within the cave of Altamira (Spain). Included in Marina Sáez's PhD thesis (2020), these analyzes made it possible to highlight the role of soil water content in the dynamics of CO_2 and ^{222}Rn in the micro-atmosphere of the cave, and to write a publication [4] and two news [11-12]. With the Equidy project, new analyzes have enabled another quite unexpected results [0]: (1) Obtain a new model of CO_2 coupled to humidity and temperature outside of the cave, (2) show that it is possible to monitor the CO_2 content of the cave from space, (3) build scenarios of the past and the future (1950-2100) considering the number of visitors and various climatic scenarios. Results show that the prehistoric parietal paintings of the cave will be endangered again. It is expected to get the paper published very soon.

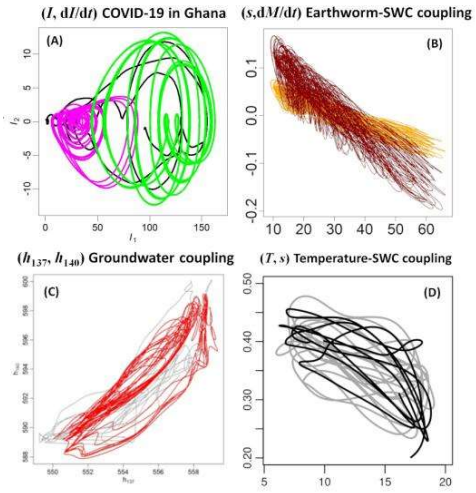

Fig. 1: Phase portraits for COVID-19 in Ghana (A)*, Earthworms activity coupled to the soil water content (SWC)* (B)*, the groundwater levels coupling* (C)*, Temperature-SWC coupling* (D).

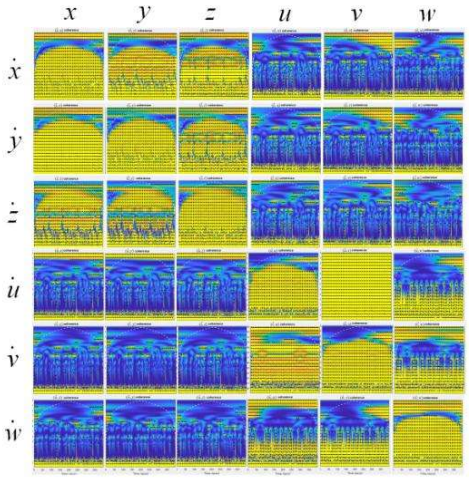

Fig. 2: Causal wavelets applied to six variables of two independent chaotic systems, the Rössler-76 system (x,y,z) *and the Nose-Hoover system* (u,v,w)*. Maximum (yellow) vs. minimum (blue) coherence.*

The extraction of dynamical equations directly from observational time series has become a hot topic. Several tools have been developed for this difficult task, most of them were not able to extract numerically stable models from observational time series. GPoM tool makes an exception since numerous models have been obtained with it since 2011. The EQUIDY project had enabled to improve its capacity further by obtaining new models [16]. The model for COVID-19 shown in Fig. 1A revealed a bi-stable dynamics which can have important consequence on mitigation measures; The one for earthworms reveals a nontrivial coupling with the soil water content in Viêt Nam (1B); A very complex coupling was unveiled between groundwater levels in the Central Highlands, Viêt Nam (1B); And finally, another complex coupling between the microatmosphere of the Altamira cave (Spain) and surface climatic variables was discovered (1D). A new approach for detecting the couplings, the causal wavelets, was also investigated. It was tested to several sets of variables generated by dynamical systems under various conditions of (directional) couplings. Fig.2 shows that the tool can be very powerful to detect nontrivial coupling even when the variables are highly uncorrelated. These results are very promising in itself. It may also become an efficient tool for preselecting the variables before applying equation extraction when the datasets are too large.

Future of the project *Finalize the publication on the causal wavelets to illustrate its interest. Communicate on the potential of GPoM tools in order to make its use common. To initiate training in their use (PSF). The submission of an ANR project is envisaged. The co-supervision of a new thesis is planned with the* ***Univ. of Valencia****.*

5 publications (+ 4 communications)

[0] 2022 Sáez M. et al., Dynamics of a cave CO_2 concentration: scenarios from 1950 to 2100, *Scient. Rep.*, **Under Revision**.
[1] 2022 Mangiarotti S. & Le Jean F., Chaotic attractors captured from remote sensing time series for the dynamics of cereal crops, *JDEA*, 1-23. https://doi.org/10.1080/10236198.2022.2152336
[2] 2022 Thenon N., Peyre M., Huc M., Touré A., Roger F. & Mangiarotti S., Covid-19 in Africa: underreporting, demographic effect, chaotic dynamics, and mitigation strategy impact, *PLoS Neglected Tropical Diseases*, 16, **9**, e0010735. https://doi.org/10.1371/journal.pntd.0010735
[3] 2021 Mangiarotti S., Fu E., Jouquet P., Tran M.T., Huc M. & Bottinelli N., Earthworms activity and its coupling to soil dynamic: a deterministic analysis, *Chaos*, 31, 013134. https://doi.org/doi:10.1063/5.0029969
[4] 2021 Sáez M., Mangiarotti S., Cuezva S., Fernandez-Cortés A., Molero B., Sanchez-Moral S. & Benavente D., Global models for CO_2 and ^{222}Rn concentrations in the Cave of Altamira, *Theoretical and Applied Climatology*, **143**(1), 603-626. https://doi.org/10.1007/s00704-020-03440-9
[5] 2020 Mangiarotti S., Peyre M., Zhang Y., Huc M., Roger, F., Kerr Y., Chaos theory applied to the outbreak of Covid-19: an ancillary approach to decision-making in pandemic context, *Epidemiology & Infection*, **148**, e95, 1-9. https://doi.org/10.1017/S0950268820000990

9 news

[6] 2022 « L'Afrique moins touchée que l'Europe, vraiment? » par Serge Cannasse, ***Univadis***, 21 Octobre 2022. COVID-19 : L'Afrique moins touchée que l'Europe, vraiment ? | Univadis
[7] 2022 « Epidémie de COVID-19 en Afrique : quelles spécificités » by **S. Mangiarotti**, A. Touré, F. Roger & M. Peyre, ***The conversation***, 11 Octobre 2022. Épidémie de Covid-19 en Afrique : quelles spécificités ? (theconversation.com); *English version:* « Covid-19 epidemic in Africa: what specificities? », ***Le journal 2 l'Afrique***, 12 Octobre 2022. Covid-19 epidemic in Africa: what specificities? (lejournaldelafrique.com)
[8] 2021 « Qu'est-ce qui fait bouger les vers de terre ? » by **S. Mangiarotti**, P. Jouquet & N. Bottinelli. ***Le courrier de la nature***, Juillet-Août, no **329**, 11-13, 2021.
[9] 2021 « What makes earthworms move ? » ***Multitemp OMP***, 30 Janvier 2021. https://labo.obs-mip.fr/multitemp/what-makes-earthworms-move
[10] 2021 « La dynamique des lombrics relève de la théorie du chaos » by Olivier Blot for ***IRD'mag***, 22 janvier 2021. https://lemag.ird.fr/fr/la-dynamique-des-lombrics-releve-de-la-theorie-du-chaos
[11] 2020 « Modelos caóticos de baja dimensión para la micro-atmósfera de la cueva prehistórica de Altamira (España) » ***Multitemp OMP***, 31 Octobre 2020. https://labo.obs-mip.fr/multitemp/modelos-caoticos-para-la-micro-atmosfera-de-altamira
[12] 2020 « Des modèles chaotiques pour la micro-atmosphère de la grotte d'Altamira » ***Actualités INSU***, 28 octobre 2020. https://www.insu.cnrs.fr/fr/cnrsinfo/des-modeles-chaotiques-pour-la-micro-atmosphere-de-la-grotte-daltamira
[13] 2020 « Covid-19 | Using chaos theory to predict the course of the epidemic » ***News Cirad***, 20 mai 2020. https://www.insu.cnrs.fr/fr/cnrsinfo/la-theorie-du-chaos-appliquee-lepidemie-de-covid-19
[14] 2020 « La théorie du chaos appliquée à l'épidémie de Covid-19 » ***Actualités INSU***, 15 mai 2020. https://www.insu.cnrs.fr/fr/cnrsinfo/la-theorie-du-chaos-appliquee-lepidemie-de-covid-19
[15] 2020 « Bulletin GPoM epidemiologic » ***Actualités OMP***, 9 février 2020. https://labo.obs-mip.fr/multitemp/bulletin-gpom-epidemiologic

[16] Mangiarotti S., Le Jean F., Chassan M., Drapeau L., & Huc M., GPoM: Generalized Polynomial Modelling, *Comprehensive R Archive Network*. Dépôt V1.4 mis à jour le 16/06/2023 avec la dernière version des codes, ceux utilisés pour Equidy. PI. Sous licence CeCILL-2.

Package téléchargeable sur le site du CRAN au lien : https://CRAN.R-project.org/package=GPoM