FINAL REPORT PROGRAM LEFE

Program LEFE/ action(s) MANU	Project Title Dynamical INdicators for CLImate Change (DINCLIC)	Years 2019 – 2022

PI name, email and lab: Davide FARANDA, davide.faranda@lsce.ipsl.fr LSCE Participating Laboratories : SPEC-CEA Saclay;CPT Marseille; Department of Mathematics, U Hokkaido, JP	Contribution to *ANR-TERC BOREAS, H2020 XAIDA, H2020 MSCA ITN EDIPI, MITI-CNRS project UNDERPIN* Other funding sources : the above listed projects

Context: *Cold waves, heat waves, extra-tropical cyclones, are extreme climate events associated with rare or persistent atmospheric circulation patterns and/or caused by thermodynamic effects. The dynamic component is difficult to characterize because it relies on chaotic properties of the atmospheric circulation, a challenge for scientists.*

Objectives / scientific questions: The goal of DINCLIC is to develop metrics based on dynamical systems theory to separate the thermodynamic from the dynamical contribution to the origin of extreme events. DINCLIC determines whether the changes in frequency and intensity observed in future climate simulations are related to changes in atmospheric circulation or rather to thermodynamic effects induced by the greenhouse effect.

Main results: In order to achieve the goals of DINCLIC, we have used tools form extreme Value Theory (EVT) in the study of climate data. This has allowed to compute recurrence times statistics for climatic systems, but also to provide important information on the stability and the complexity of a particular climatic state. This information is contained in indicators that can be estimated via EVT-based methods. Recently, we have extended this approach to observations computed along the trajectory of a collection of measurements at different locations of a spatially extended system or even delay coordinate observables used in embedding techniques. For certain kinds of observations, the approach has allowed us to recover information on the underlying system. One of the main achievements of DINCLIC was to demonstrate how impacting climate events correspond to unstable fixed points of the attractor by means of dynamical systems metrics capable of informing about the predictability (local dimension), the persistence and the synchronization (extremal index) of physical states. These metrics have recently provided insights on a number of geophysical phenomena, including transitions between transient metastable states of the mid-latitude circulation [Faranda et al. 2019, ESD], palaeoclimate attractors [Clim. Dyn, Messori & Faranda 2021, Clim. Past] slow earthquake dynamics [Gualandi et al. 2020, Science Adv.] and changes in mid-latitude atmospheric predictability under global warming [Faranda et al. 2019 Nature Comm.]. Recent theoretical developments in that direction have been made in Haydn et al (2020), who considered arbitrary regions of the attractor. The universal limit law is a compound Poisson distribution that is modulated by the cluster size distribution. In the case where the target set is a ball, the size of the blocks is geometrically distributed, whose parameter is given by the Extremal Index, yielding a Poyla-Aeppli distribution (Cabi et al. 2021). We propose a detailed study of this matter in the context of blocking detection. Faranda et al. (2019, ESD) have shown that blocking events can be studied in spatially extended dynamical systems: the CLMs. In this model, blocking is seen as a subgroup of synchronizing sites, and a subgroup with motions that are not synchronized with the first group, as the Chimera States defined above.

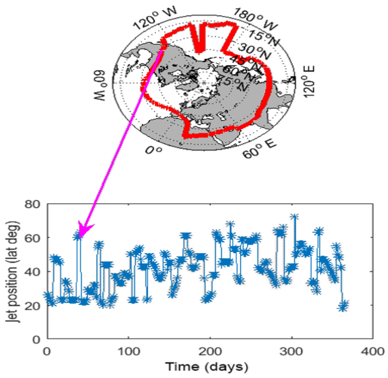

Figure 1

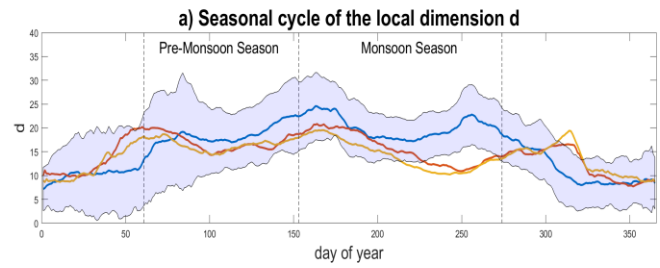

Figure 2

In earlier work, Faranda and others showed that dynamical systems techniques can now be used to yield effective low-dimensional dynamics, as long as the observables chosen reflect key symmetries of the system and one treats small-scale (sub-grid) dynamics as stochastic perturbations. In the new paper, the authors use these results to develop a minimal model of the effective dynamics of the mid-latitude jet. The jet model is based on a coupled map lattice, each element of which reflects the dynamics of the jet at a given longitude (**Figure 1**). As the researchers demonstrate, this model is useful for exploring a range of possible behaviors which may have appeared in past climates, and could appear again in future. Using the model, they offer an evaluation of key dynamical features of the jet, namely its stability, the statistics of splitting or breaking and the response to topographical features. (For more information see Faranda et al 2019 ESD).
In a recent Technical Note, Messori and Faranda consider propose a framework for efficiently processing and interpreting large amounts of model output to compare different simulated palaeoclimates. Their approach is grounded in dynamical systems theory, and allows researchers to characterise the dynamics of a given dynamical system – the atmosphere, for example – using three one-dimensional metrics. A first metric estimates the persistence of instantaneous states of the system. A second metric, which they call the "local dimension," provides information on how the system evolves toward or away from instantaneous states.

***Future of the project**:* The project has given rise to several international and national collaborations between the participants. It has allowed the PI to obtain the ANR-ERC grant "BOREAS" for the study of cold-spells over Europe. The dynamical indicators developed in DINCLIC are also used in the European projects H2020, XAIDA "eXtreme events: Artificial Intelligence for Detection and Attribution" where D Faranda is coordinating the WP8 , the MSCA ITN project EDIPI (european weather Extremes: DrIvers, Predictability and Impacts) where D Faranda is coordinating training and two students (M Ginesta and F Lopez-Marti) are using the dynamical indicators defined in DINCLIC. Another project that is continuing the same interdisciplinary collaboration of DINCLIC and it has recently awarded from the MITI-CNRS to D Faranda as PI in 2022 is UNDERPIN: UNDERPIN bridges statistical physics, statistics, dynamical systems and climate sciences to study persistent, high-impact climate extremes such as heatwaves, cold-spells and slow-moving cyclones.

Publications where DINCLIC is explicitly acknowledged:

- Faranda, D., Sato, Y., Messori, G., Moloney, N. R., & Yiou, P. (2019). Minimal dynamical systems model of the northern hemisphere jet stream via embedding of climate data. Earth System Dynamics, 10(3), 555-567.

-Faranda, D., Vrac, M., Yiou, P., Jézéquel, A., & Thao, S. (2020). Changes in future synoptic circulation patterns: consequences for extreme event attribution. *Geophysical Research Letters*, *47*(15), e2020GL088002.

-Faranda, D., Vrac, M., Yiou, P., Pons, F. M. E., Hamid, A., Carella, G., ... & Gautard, V. (2021). Enhancing geophysical flow machine learning performance via scale separation. *Nonlinear Processes in Geophysics*, *28*(3), 423-443.

-Faranda, D. (2020). An attempt to explain recent changes in European snowfall extremes. *Weather and Climate Dynamics*, *1*(2), 445-458.

- Faranda, D., Messori, G., & Yiou, P. (2020). Diagnosing concurrent drivers of weather extremes: application to warm and cold days in North America. *Climate Dynamics*, *54*(3), 2187-2201.

- Yiou, P., Faranda, D., Thao, S., & Vrac, M. (2021). Projected changes in the atmospheric dynamics of climate extremes in France. *Atmosphere*, *12*(11), 1440.

-Messori, G., & Faranda, D. (2021). Characterising and comparing different palaeoclimates with dynamical systems theory. *Climate of the Past*, *17*(1), 545-563.

-Faranda, D., Messori, G., Jézéquel, A., Vrac, M., & Yiou, P. (2021). Atmospheric circulation compounds anthropogenic warming and its impacts in Europe. *Nature Climate change (in review)*

- Faranda, D., Messori, G., Yiou, P., Thao, S., Pons, F., & Dubrulle, B. (2021). Detecting intense hurricanes from low resolution datasets via dynamical indicators*. Monthly weather review, (in review)*

-Faranda, D., Bourdin, S., Ginesta, M., Krouma, M., Messori, G., Noyelle, R., ... & Yiou, P. (2022). A climate-change attribution retrospective of some impactful weather extremes of 2021*. Weather and Climate Dynamics Discussions, 1-37.*

International communications: DINCLIC has motivated about 20 international communications in conferences such as EGU, AGU, APS. Furthermore, the topics of DINCLIC are covered by the session "Extremes in geophysical sciences: drivers, methods and impacts quantification", organized by D Faranda for the 4th consecutive year in 2022

***Education**:* D Faranda has supervised 5 master students, and he is now supervising 3 PhD students (M Ginesta, R Noyelle and N Malhomme) working on the dynamical indicators defined in DINCLIC.