AO INSU 2019
Section « Océan-Atmosphère » - MANU - LEFE

Description du projet

(1) Nom du porteur du projet et laboratoire de rattachement

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(2) Titre du projet

<u>Dynamical INdicators for CLImate Change</u>
<u>(DINCLIC)</u>

(4) Mots clés

Climate dynamics, Dynamical Systems, Statistical Mechanics, Extreme Events

(5) Intérêt scientifique, contexte et état de l'art

In 2012, a storm generated heavy snowfalls and unusual low temperatures at several locations in central Italy (*e.g.* -7 C in Rome). The severe damages caused by the storm, as well as the disruption of practically all the transportation means in central Italy, suggest that there is still room for optimizing the societal response to these events. On that occasion, all the media recalled the 1956 cold wave that struck the same area with similar effects 50 years before. The similarities in the static position of cyclonic and anticyclonic patterns between the two maps of Figure 1 suggest that atmospheric *dynamics* drove these two events. However, extremely low temperatures were already recorded over the Balkans several days before. Can those weather patterns result from the *thermodynamics* needed to evacuate cold air towards the Mediterranean basin?

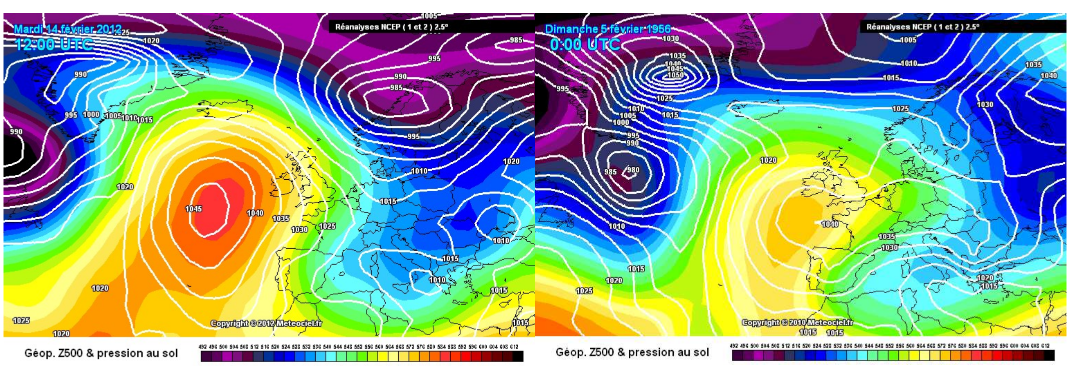

Figure 1: Two extreme winter weather analogues: Left panel: Feb 14th, 2012. Right panel: Feb 5th 1956. The color scale refers to the geopotential height at 500hPa, the white levels to the ground pressure.

In order to find the physical drivers of such events, atmospheric scientists study their dynamics and thermodynamics with an approach based on case-study (e.g. the 2003 heatwave over Europe [2] or the extreme precipitations over UK in winter 2013/2014 [3]). To improve early warning systems and to study the effect of anthropogenic forcings on extreme events, it is useful to generalize the results found in one case to a class of events.
The attribution of extreme events necessitates the computation of the probability that an observable (e.g. mean or peak temperature over a country or locally, cumulated precipitation over a region, etc.) exceeds a high threshold, and how such a probability evolves with climate change [4]. Those probabilities are linked to return times of rare events. Determining the relation between such probabilities and physical mechanisms (e.g. the atmospheric circulation) has been deemed to be a crucial challenge in order to understand how mean climate change affects extreme events [5,6].
A natural alley of investigation is the study of the co-occurrences of atmospheric thermodynamic and dynamical patterns for assessing their relative contributions to the probability of event occurrence : Extreme value theory [7,8,9,10] gives the probability that the system enters for the first time a small region of the phase space (rare event) after a certain amount of time [11]. This allows to characterize the attractor of complex systems such as climate. The attractor is the geometrical object that hosts all the trajectory of a system. The geometry of this object can be characterized by dynamical indicators such as the fractal dimension, the Lyapunov exponents, the Entropy, the rate of separation of nearby trajectories. This indicators can be defined locally on the attractor: for climate, this means the possibility to define them for class of extreme events such as cold spells, heatwaves or storms. We have shown the feasibility of this approach in [13,14]. Given the limited samples, a question to assess the validity of the indicators for climate fields, is whether the presence of extreme events influence the convergence of the indicators towards their expected values. This is a large deviations question: those indicators could take huge excursions from their typical values, but with (usually exponential small), probability. Hence, they could be still useful for the characterization of climate fields.
Our ongoing investigations suggest that not only asymptotic results but also finite time indicators can be derived in this theoretical framework. This is a promising new field of research which we begin to investigate quite recently and which allows to quantify in space (large deviations) and in time (extreme value distributions), the occurrence of (exceptional) rare events [15]. We plan to develop a general theory for large class of systems and to study applications to concrete situations in climate settings.

(6) Objectif général et questions de recherche traitées

The goal of DINCLIC is to determine the contributions of dynamics and thermodynamics patterns to rare events in conceptual atmospheric systems via the dynamical indicators (local dimensions, local stability). The applicability to real systems (reanalyses, observations, general circulation models, regional climate models) also will be assessed.
DINCLIC combines results from the dynamical systems theory and the extreme value theory to disentangle the dynamical and thermodynamic contributions to the occurrence of extreme events**.** To achieve the main goal, DINCLIC needs to:

i) Define reliable metrics to classify by rarity, persistence and predictability of atmospheric flows.

ii) Use large samples of extremes issued from control runs of CMIP5, CMIP6 simulations as well as in turbulence dataset available in collaboration with SPEC-CEA to compute the dynamical systems metrics and assess uncertainties.

iii) Quantify changes in occurrence, frequency and intensity of extremes in a changing climate.

(7) Plan de recherche, méthodologie et calendrier de réalisation

The project is divided into three tasks dealing each with the objectives outlined before:

-**Task** 1 *(PI, Vaienti, months 1-18)*: Adapt theoretical and practical results from multivariate statistical analysis to the analysis of co-recurrences of extreme weather configurations via extensions of the dynamical systems Freitas-Freitas-Todd theorem [11] to multivariate fields. The definition of dynamical systems indicators for compound climate extreme events, implies the development of new indicators, to quantify the probability that two distinct patterns (e.g. temperature and sea-level pressure over a certain region) occur at the same time. This will be useful to determine the connection between circulation and thermodynamics of atmospheric extreme events. So far, our research activity has been devoted to the development of theoretical and numerical tools to study extremes as rare and persistent events of dynamical systems trajectories. The results we have obtained are based on a methodology which combines the statistical tools of EVT with the Poincaré recurrence theorem and the fractal theory [11,12,13]. We have already applied this framework to simple conceptual models and proven the relevance to analyze climate datasets [14].
Deliverables*:* scientific publications containing the definition of an indicator of co-recurrence of dynamical and thermodynamic analogues and case studies of specific extreme events classes (M16).

-**Task** 2: Verify the sensitivity of the dynamical indicators to attractors obtained under different forcing in conceptual models and turbulent laboratory flows from SPEC-CEA von Karman experiment where the parameters are changed abruptly or smoothly *[PI, Yiou M13-M24].* The starting point of these investigations was to recognize extreme events as configuration visited rarely by a typical trajectory of the system [11]**.**
Deliverables*:* -A set of methods and numerical tools to detect changes in attractors' properties (M24).

-Task 3 (*PI, Yiou, Vaienti: Months M13:M36)*: Once the sensitivity is proven, study the change in dynamical properties of atmospheric attractors using the long CMIP5,CMIP6, CORDEX runs. The modifications induced by changes in external forcing can be different: the attractor can rotate, translate, lose or gain parts (bifurcate) depending on the forcing. This work package is the one presenting the highest risk factors and we will work all together on this issue. If theoretical results are too difficult to obtain, DINCLIC will use a bottom-up approach by analyzing the robust change on extreme events numerically.
Deliverables: A complete assessment (report) of the changes in the dynamical properties of the atmospheric variables in past, present and future climate (M36).

(8) Résultats attendus

DINCLIC stems from fundamental questions in climate science, which demand an appropriate physical mathematical framework. DINCLIC's results will provide new opportunities for the fine analysis of extreme climate events, in terms of space and timescale, without running costly climate simulations and using supercomputers. It will design and distribute to the climate science community an open source toolbox for the dynamical analysis of climate extremes, with a robust assessment of their properties. The innovation potential of this project is rather high because we go from dynamical system theory to an application toolbox, and a semi-automatic detection and attribution of extreme events. Although the project mainly focuses on atmospheric fields, the methodology itself can be used on any sequences of states of a system (e.g. coupled or ocean models, medical imagery, astrophysical applications) for which extensive databases of simulations are also available. The generic nature of the theoretical tools developed within the project will make them suitable for all the applications where time-series of vector fields are available.

(9) Références bibliographiques principales des proposants

References of the applicants

(a) Davide Faranda and Sandro Vaienti. A recurrence-based technique for detecting genuine extremes in instrumental temperature records. *Geophysical Research Letters*, 40:1-5, 2013.

(b) Davide Faranda, Giacomo Masato, Nicholas Moloney, Yuzuru Sato, Berengere Dubrulle, Francois Daviaud, and Pascal Yiou. The switching between zonal and blocked mid-latitude atmospheric circulation from a dynamical systems perspective. *Climate Dynamics*, 1-13, 2015.

(c) Davide Faranda, Yuzuru Sato, Brice Saint-Michel, Cecile Wiertel-Gasquet, Vincent Padilla, Berengere Dubrulle, & Francois Daviaud. Stochastic chaos in a turbulent swirling flow. *Physical review letters,* 119, 014502, *2017.*

(d) Davide Faranda & Sandro Vaienti. Correlation dimension and phase space contraction via extreme value theory. *Chaos*, 28, 0411103, 2018

(e) David Rodrigues, M Carmen Alvarez-Castro, Gabriele Messori, Pascal Yiou, Yoann Robin, Davide Faranda. Dynamical properties of the North Atlantic atmospheric circulation in the past 150 years in CMIP5 models and the 20CRvc2 reanalysis. *Journal of Climate*, 1-18, 2018.

(f) Valerio Lucarini, Davide Faranda, Ana Cristina Gomes Monteiro Moreira de Freitas,Jorge Miguel Milhazes de Freitas, Mark Holland, Tobias Kuna, Matthew Nicol, Mike Todd, Sandro Vaienti. Book: Extremes and Recurrence in Dynamical Systems. ISBN 978-1-118-63219-2, 312 pages, Wiley, 2016.

References of the proposal

[1] Yiou P et al. *Geophysical Research Letters* 34(21) (2007).
[2] Trigo et al *Geophysical research letters*, *32*(10) (2005).
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[4] Wilcox et al. *Climate Dynamics* 1-19 (2017).
[5] Trenberth et al. *Nature Climate Change* (2015)
[6] Shepherd et al. *Current Climate Change Reports* (2)28:38 (2016)
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[11] Lucarini V et al. *Extremes and Recurrence in Dynamical Systems*. (Wiley, 2016).
[12] Faranda D et al. *Nonlinearity* 26.9: 2597 (2013).
[13] Faranda D et al. *Climate Dynamics* 1-13 (2016).
[14] Faranda D et al. Scientific Reports (7) 41278 (2017).
[15] Ragone F et al. PNAS (2017).

(10) Participation effective, prévue ou envisageable à d'autres programmes de recherche régionaux, nationaux et européens sur les mêmes problématiques

DINCLIC explores fundamental issues of the *attribution* of extreme events. It complements *climate service* projects (Convention de Service Climatique (COSC), French Ministry of Environment; EUPHEME, Copernicus). The results of DINCLIC will be applied to the case studies outlined in those national and European projects.Some of those fundamental issues come in support of P. Yiou's ERC grant (A2C2: 2014-2019) that explored the statistical properties of the atmospheric circulation during rare events. The mathematical and statistical developments of DINCLIC were deemed to be priorities in one of the research objectives of IPSL ("internal and forced variability").

(11) Compléments

The project is framed in a national and international community of mathematicians and physicists working in the field of dynamical systems and statistical mechanics and their application to climate sciences. This community, whose core is constituted by the co-authors of the book [11], is active with conferences, joint publications and international meetings. The budget requested for travels will be mostly used to keep and strengthen the contacts with this community. DINCLIC will be the starting point for building a strong applied and theoretical team where the study of extreme events is supported by dynamical systems and statistical physics indicators. The long-term vision of the team is to be open to the mathematical community where powerful theoretical tools are developed but not always immediately transformed in useful indicators to study physical phenomena. The team activity will also be driven by the societal demand of better understanding the properties of extreme events. In a changing climate, the occurrence of black swans (e.g. summer 2003 European heatwave and summer 2017 hurricanes' season) will be a continuous reservoir of fuel for such novel scientific approaches. The PI is the convener of an EGU session entitle "Dynamical Extremes in climate science' whose topics are strongly related to this project. The budget request contains an explicit request for participating at EGU and continuing organizing this session as an occasion to exchange with other scientists working in the field.