Physics of Complex Systems and Global Change

French-German WE-Heraeus-Seminar

10 - 15 March 2024

at the

École de Physique
Les Houches, France

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the French-German WE-Heraeus-Seminar "Physics of Complex Systems and Global Change:

Complex systems are underlying some of the major issues of global change in the 21st century, that are jeopardizing a sustainable existence on our planet. From atmospheric and ocean dynamics to climate change, from ecosystems to the loss of biological diversity, or from energy consumption to economic crises - it is a characteristic that these systems are strongly cross-linked and influence each other. Complexity science and dynamical systems provide general frameworks for the characterization, analysis, and forecast of such systems and are offering methods for the study of extreme events and tipping points.

This binational workshop will bring together scientists from climate sciences and ecology with experts in complexity science in order to discuss topical challenges of global transformations and to foster collaborations not only between the two countries, but also between the various fields involved.

Introduction

Scientific Organizers:

Prof. Dr. Theo Geisel	Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany E-mail: geisel@ds.mpg.de
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Registration:

Arrival is only possible from 3:00 pm on Sunday. It is important not to arrive on the site any earlier, as the buildings are closed before this time. Upon arrival please go to the lobby of the Cécile DeWitt building:

Program

Program

Sunday, 10 March 2024

From 15:00	Arrival	
19:30	*DINNER*	

Monday, 11 March 2024

07:45 – 08:45	*BREAKFAST*	
09:00 – 09:15	Hugues Chaté & Theo Geisel	**Welcome and Introduction**
09:15 – 09:30	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
09:30 – 10:30	Ricarda Winkelmann	**Ice matters: The long-term legacy of short-term climate (in)action**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 12:00	Ulrike Feudel	**Critical transitions in complex systems: theory and applications to climate and ecosystem dynamics**
12:30 – 14:00	*LUNCH*	
14:00 – 17:00	Discussion Groups	
17:00 – 18:00	TEA BREAK	
18:00 – 19:30	**Flash Talks & Poster Session**	
19:30	*APÉRITIF & DINNER*	
21:00	**Poster Session, continued**	

Program

Tuesday, 12 March 2024

07:45 – 08:45	*BREAKFAST*	
09:00 – 09:40	Freddy Bouchet	**New ways for dynamical prediction of extreme heat waves, extremes of renewable electricity production, and abrupt climate change: rare event simulations and machine learning**
09:40 – 10:20	Holger Kantz	**Long range temporal dependence in atmospheric data**
10:20 – 10:40	*COFFEE BREAK*	
10:40 – 11:20	Jérôme Chave	**Is locking up carbon in forests an affordable strategy for mitigating carbon emissions?**
11:20 – 12:00	Fabien Maussion	**Mountain glaciers are disappearing faster than ever observed. What are the remaining big questions in glaciology?**
12:10	*Conference Photo*	
12:30 – 14:00	*LUNCH*	
14:00 – 17:00	**Discussion Groups**	
17:00 – 18:00	*TEA BREAK*	
18:00 – 18:20	Lorina Buhr	**The concepts of irreversibility and reversibility in research on anthropogenic environmental changes: a systematic literature review**
18:20 – 18:40	Bryony Hobden	**Dansgaard-Oeschger events: Challenges of predicting abrupt shifts in multiscale systems**
18:40 – 19:20	José Halloy	**The basic concepts of the physics of complex systems illuminate questions of sustainability**
19:30	*DINNER*	
21:00	Fabien Maussion	**From glaciers in Chamonix to the globe: quantifying the ice cost of our greenhouse gas emissions**

Program

Wednesday, 13 March 2024

07:45 – 08:45	*BREAKFAST*	
09:00 – 12:00	**Optional excursions or discussion groups**	
12:30 – 14:00	*LUNCH*	
14:00 - 16:00	Discussion Groups	
16:10 - 16:50	Joachim Peinke	**Non-equilibrium thermodynamics of extreme events in wind turbulence and water waves**
16:50 – 17:30	Claudia Brunner	**Wind turbine flows: how atmospheric conditions affect tip vortex decay into turbulence**
17:30 – 18:00	*TEA BREAK*	
18:00 – 18:40	Silvia De Monte	**Phytoplankton communities: from strong interactions to macroecological patterns**
18:40 – 19:20	Marc Timme	**Fluctuation-responses and tipping in strongly perturbed nonlinear systems**
19:30	*DINNER*	
21:00	**Optional Poster Session**	

Program

Thursday, 14 March 2024

07:45 – 08:45	*BREAKFAST*	
09:00 – 09:40	Pascal Yiou	**Statistical challenges to model and simulate climate extremes**
09:40 – 10:20	Florian Sévellec	**Millennial chaotic variability of the Atlantic overturning circulation in an Idealized model**
10:20 – 10:40	*COFFEE BREAK*	
10:40 – 11:20	Günter Radons	**Effects of delay variations in dynamical systems**
11:20 – 12:00	Jin Song von Storch	**A theory of randomness**
12:30 – 14:00	*LUNCH*	
14:00 – 17:00	Discussion Groups	
17:00 – 18:00	*TEA BREAK*	
18:00 – 18:40	Aglaé Jézéquel	**Broadening the scope of anthropogenic influence in extreme event attribution**
18:40 – 19:00	Johannes Kassel	**Utilizing long-memory and teleconnections for stochastic forecasts of winter temperature extremes**
19:00 – 19:20	Caterina Mosto	**Topological tipping in a low-order Atlantic Meridional Overturning Circulation model**
19:30	*CONFERENCE DINNER & POSTER PRIZES*	

Program

Friday, 15 March 2024

07:45 – 08:45	*BREAKFAST*	
09:00 – 09:40	Angelika Humbert	**Complexity of ice sheets - physical processes of the Greenland Ice Sheet**
09:40– 10:20	Thierry Penduff	**Atmospherically-paced chaotic ocean variability: towards a dynamical system viewpoint**
10:20 – 10:40	*COFFEE BREAK*	
10:40 – 11:20	Bjorn Stevens	**The standard model of climate & what it's missing**
11:20 – 12:00	Final discussion	
12:30 – 14:00	*LUNCH*	

End of the seminar and departure

Posters

Posters

Simon Anghel	**Deep Learning Methods Applied to All-Sky Cloud Coverage Estimation**
Jan Timo Bachmann	**A generalized model for mutualism reveals the effect of network topology and size on the dynamical stability of mutualistic networks**
Alexandre Barboni	**How do mesoscale eddies evolve in time ? Numerical simulation accuracy compared to observations**
Léo Cazenille	**Earth System surrogate models via Quality-Diversity optimization and Physics-Informed Neural Networks**
Misha Chai	**A single-species population model**
Ryan Deeley	**The increased likelihood of plankton community changes following marine heatwaves**
Hairu Ding	**Links between subtropical high-pressure systems and stratocumulus clouds variation**
Hongdou Fan	**Delayed and transient impacts of the North Atlantic Oscillation on subdecadal variability of Norwegian Sea temperature**
Juan Giral Martínez	**Interplay of structure and randomness in complex ecological communities**
Moshir Harsh	**Capturing intrinsic noise in the stochastic dynamics of discrete populations on networks**
Dominic Hillenkötter	**Sensitivity Analysis of the Lorentz Energy Cycle in the ICON-O Model**
Clara Hummel	**Variability of the Arctic summer sea ice border on its way up North**

Posters

Julius Mex	**The origin of the observed global temperature extremes in 2023**
Daniela Moreno	**Dynamics of the center of wind pressure: From large-scale turbulent structures to loads on a wind turbine**
Andreas Morr	**Anticipating critical transitions in multi-dimensional systems driven by time- and state-dependent noise**
Benjamin Musci	**Enstrophy conditioned extreme-event statistics and their morphology**
Pauleo Nimtz	**Varieties of Democracy in Times of Global Change: The V-DEM Dataset, Dynamics of Democracies, and Impact of Global Events**
Paula Pirker-Díaz	**Modelling dynamics of political regime types in the 20th century**
Raphael Römer	**Characterising Edge States: Measures on chaotic non-attracting invariant sets**
Lucas Rudelt	**Where is the error? Self-organization and unsupervised learning in neural networks through dendritic error computation**
Agustin Somacal	**State estimation of urban air pollution with statistical, physical, and super-learning graph models**
Samudrajit Thapa	**Detecting the local and global variations of the long-range dependence in daily temperature data**
Moritz Thümler	**Fluctua on-Responses and Tipping in Strongly Peturbed Systems**
Victor Valadao	**Non-equilibrium spectral correction in SQG turbulence**

Posters

Matthias Wächter	**Stochastic analysis of jump noise along with Langevin noise in real-world data sets**
Martin Wagner	**Langevin analysis of wind turbine control parameters**
Meng Wu	**Variational Integrators for Stochastic Hamiltonian Systems on Lie Groups**
Arim Yoon	**Impact of Amazon Deforestation on Precipitation in a Strom-resolving Global Climate Model**
Tingyu Zhao	**Denoising and debiasing of complex real-world networks**

Abstracts of Talks

(in alphabetical order)

New ways for dynamical prediction of extreme heat waves, extreme of renewable electricity production, and abrupt climate change: rare event simulations and machine learning

B. Cozian[2], G. Milosevich[2], C. Le-Priol[1], F. Ragone, C. Herbert[2] and F. Bouchet[1]

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[2] ENSL, CNRS, Laboratoire de Physique, Lyon, France

In the climate system, extreme events or transitions between climate attractors are of primarily importance for understanding the impact of climate change. Recent extreme heat waves with huge impact, or period very low production of renewable energy in the electricity system are striking examples. However, a key challenge is the lack of data, because these events are too rare and realistic models are too complex.

I will discuss new algorithms and theoretical approaches, based on rare event simulations, and machine learning for stochastic processes, which we have specifically designed for the prediction of the committor function (the probability of the extreme event to occur). To illustrate the performance of these tools, I will discuss results for the study of midlatitude extreme heat waves and the extremes of renewable energy production in relation with the resilience of the electricity system.

I will also briefly explain how the same rare event simulation and machine learning tools can be used to study rare transitions between different states of the climate system, leading to abrupt climate change. I will explain past works in this direction and current research projects.

References

[1] F. Ragone, J. Wouters, and F. Bouchet, Proceedings of the National Academy of Sciences, vol 115, no 1, pages 24-29, https://doi.org/10.1073/pnas.1712645115, and arXiv:1709.03757, [pdf] (2018)

[2] G. Miloshevich, B. Cozian, P. Abry, P. Borgnat, and F. Bouchet, Phys. Rev. Fluids 8, 040501, doi.org/10.1103/PhysRevFluids.8.040501 and *arXiv:2208.00971*, [pdf] (2023)

[3] D. Lucente, J. Rolland, C. Herbert and F. Bouchet, J. Stat. Mech. 083201, *arXiv:2110.05050*, [pdf] (2022)

[4] B. Cozian, C. Herbert, and F. Bouchet, *arXiv:2311.13526*, [pdf] (2024)

Wind turbine flows: how atmospheric conditions affect tip vortex decay into turbulence

C. E. Brunner[1]

[1]*Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany*

Variable Density Turbulence Tunnel [1]

Wind energy plays a crucial role in clean energy generation. However, wind turbines operate in highly turbulent atmospheric flows, where both the local meteorological conditions and the arrangement of turbines in a farm significantly impact power production. Neither their interactions with one another nor with the surrounding flow field are sufficiently understood. The fundamental challenge in the study of wind turbines lies in the large separation of scales. Wind turbines are among the largest machines ever built, spanning diameters of up to 220 m. The largest coherent structures in the turbulent atmosphere are of the same order of magnitude. Meanwhile, the smallest scales of the flow, at which the turbulence is dissipated, are O(1mm). State-of-the-art numerical simulations are nowhere near capable of resolving this range of scales. Atmospheric flows are heterogeneous in space and time, so that elucidating the underlying flow physics through field measurements alone is difficult. A key challenge in the laboratory study of wind turbines is the ability to create high Reynolds number flows at small scale. Because real wind turbines are too large to study in a laboratory, most experimental wind turbine research is conducted on scaled-down models, which typically achieve lower Reynolds numbers and thereby change the physics involved.

Here, I will present research conducted in the Variable Density Turbulence Tunnel at the Max Planck Institute for Dynamics and Self-Organization, a specialized wind tunnel that uses compressed sulfur hexafluoride to achieve high Reynolds numbers. In other words, this facility creates small-scale flows that accurately reproduce the flow physics of large atmospheric flows. I will discuss experimental data that takes a closer look at the effect of velocity shear in the atmospheric surface layer on the breakdown of the so-called tip vortices that are shed from wind turbine blades and can have profound effects on downstream turbines. Shear is well known to affect tip vortex breakdown. Here, I attempt to identify the various physical mechanisms involved by disentangling the effects of the mean velocity gradient, turbulence intensity and tip speed ratio. Understanding these mechanisms will improve our ability to model turbine-turbine interactions under varying meteorological conditions.

References

[1] E. Bodenschatz, G. P. Bewley, H. Nobach, Rev. Sci. Instrum. **85**, 093908 (2014)

The concepts of irreversibility and reversibility in research on anthropogenic environmental changes: a systematic literature review

L. Buhr[1], Auke Pols[2], D. Lenzi[3], C.E. Brunner[4], A. Staal[1], B. Hofbauer[5], B. Bovenkerk[2]

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[2] *Wageningen University & Research, Wageningen, Netherlands*
[3] *University of Twente, Enschede, Netherlands*
[4] *Max Planck Institute for Dynamics and Self-Organization*
[5]*Research Institute for Sustainability Hemholtz Centre Potsdam*

Background: The terms 'irreversible'/'irreversibility' and 'reversible'/'reversibility' have become prominent in research on anthropogenic environmental changes, including global warming, major changes in the Earth systems. Closely related to this is the investigation of tipping points, critical transitions or regime shifts in ecosystems, large-scale biodiversity, species, and ice losses. Originating from thermodynamics and dissipative physical systems, the concept of irreversibility now appears to have effectively entered environmental and ecological research. Here, irreversibility and reversibility are often used descriptively as a property of system change. However, careful reading shows that the concept is normatively laden, depending on assumptions such as the definition of the relevant timescale(s) and the undesirable system state(s), and whether it is empirically and institutionally possible and wanted to engage in efforts that prevent undesirable major environmental changes.

Methods: The paper presents the results of an interdisciplinary systematic literature review which aimed to trace the usages, semantic functions, and conceptual contexts of the concepts of irreversibility and reversibility, as well as to highlight normative implications and rhetorical strategies in the use of this terminology. For the first time, the use of the terms irreversibility and reversibility in research on anthropogenic environmental changes are systematically recorded and analysed.

Results: The review (1) shows that ir/reversibility is a key category for definitions, conceptual models, and is used as a qualifier of types of transitions, and in describing of research findings across environmental and ecological research fields; (2) reveals a range of temporal and spatial definitions of ir/reversible change. (3) The results further emphasise that the determination of the irreversibility and reversibility of changes have normative implications for intergenerational decision-making and action towards an ecologically sustainable future.

Is locking up carbon in forests an affordable strategy for mitigating carbon emissions?

Jérôme Chave[1]

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Forests are complex adaptive systems, being a collection of tree populations that grow, compete for space and depend for their survival on a myriad of mutualists, predators, pollinators and seeds dispersal. They play a vital role at recycling matter, especially carbon dioxide and water, and energy. Model inversion, and direct measurements based on forest inventories and eddy flux covariance system all converge to predict that forests absorb around a quarter to a third of fossil carbon dioxide emissions, thereby considerably slowing atmospheric warming. This finding has prompted governments, private stakeholders and others to suggest that planting trees and forest regeneration would be an essential lever to slowing emissions until new carbon-savvy technologies are mature. In essence, this model favors the emergence of a carbon market. I explore how this model is built on serious assumptions both concerning the dynamics of forests and of that of socioeconomic systems. First, are forests really capable of absorbing more carbon in the future and acting as nature-based solutions? The answer depends on the region, the type of forest (plantation or natural regrowth) and the sensitivity of forests to future climatic conditions. It will also be essential to establish and validate forest monitoring systems that are sensitive to carbon stocks, a challenge that is far from trivial. The physical basis of forest dynamics helps to understand the likelihood of forests being able to navigate to other stable states, but in spite of much research we still have an incomplete understanding of the sensitivity of forests to climatic drivers. Second, even if forests are capable of absorbing more carbon, is the ambition to shift current economies to carbon-neutral solutions realistic? Historical patterns and current trajectories of the energy mix suggest that changes in fossil energy use are regional and do not reflect the fundamental dependence of imported products on a fossil-based economy. If the only toolbox for combating climate change is based on market regulation, it is entirely possible to imagine that forests planted to reduce human-caused carbon emissions will later be converted to other uses. It is also entirely possible that the burden of ensuring the replanting of forests will be placed on the countries of the Global South, without there being any evidence that historically emitting economies will make a long-term commitment to maintaining the integrity of these carbon reservoirs. In conclusion, although carbon storage in forests appears to be an inexpensive and desirable solution for mitigating climate change, major challenges linked to the nature of forest ecosystems and that of global economic systems need to be explored. Forests are unlikely to be a silver bullet to the problem of climate change.

Phytoplankton communities: from strong interactions to macroecological patterns

S. De Monte[1,2], Emil Mallmin[2] and A. Traulsen[2]

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[2] *Max Planck Institute of Evolutionary Biology, Plön, Germany*

Phytoplankton communities are composed, as most microbial communities, by a huge number of different species that coexist despite competition for shared resources and environmental filtering [1,2].
Several mechanisms have been proposed as being key for the maintainance of high species diversity, and in particular neutral models – where the abundance of effectively identical species is determined by stochastic demography and immigration – have been succesful in reproducing observed patterns in empirical distributions of rare species [3]. When species are instread let interact, competition can instead lead to a drastic decrease in the number of co-existing species by competitive exclusion.
Recently, statistical physics models where species interactions are randomly assigned, like the Disordered Generalized Lotka-Volterra Equations, were proposed as alternative scenari allowing for extensive coexistence, and have been solved for weak and relatively uniform interactions with Dynamical Mean Field Theory.

Natural communities are however charachterized by strong and heterogenous interactions, so that species can be highly antagonistic, but also mutualistic. In this case, DMFT cannot be used to exactly solve self-consistently the equations for the ecological dynamics.
We address here the out-of-equilibrium dynamics of DGLVE with immigration [4]. Generically, this model captures characteristic features of planktonic ecology, such as boom-and bust intermittent variations, power-law distributions of non-dominant species and constant species turnover. Through such chaotic dynamics, almost complete competitive exclusion of dominant species occurs against a background of multitudes of rare ones, which come to become dominant at a later time.
An approximate ‘focal species’ effective model allows us to make sense of the apparent equivalence of species, but also of their differences. Moreover, it provides a possible explanation for the small geographical variation of abundance distributions, and offers new tools for analyzing empirical time series.

References

[1] G.E. Hutchkinson, Americal Naturalist, **95**,137 (1961)
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Critical transitions in complex systems: theory and applications to climate and ecosystem dynamics

U. Feudel[1]

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Many systems in nature are characterized by the coexistence of different stable states for a given set of environmental parameters and external forcing. Examples for such behavior can be found in different fields of science ranging from mechanical or chemical systems to ecosystem and climate dynamics. As a consequence of the coexistence of a multitude of stable states, the final state of the system depends strongly on the initial condition. Perturbations, applied to those natural systems can lead to a critical transition from one stable state to another. Those transitions are called tipping phenomena in climate science and are related to catastrophic changes in the considered system. Such critical transitions can happen in various ways [1]: (1) due to bifurcations, i.e. changes in the dynamics when external forcing or parameters are varied extremely slow (2) due to fluctuations which are always inevitable in natural systems, (3) due to rate-induced transitions, i.e. when external forcing changes on characteristic time scale comparable to the time scale of the considered dynamical system [2], (4) due to shocks or extreme events [3] and (5) due to phase-dependent transitions. We discuss these critical transitions and their characteristics and illustrate them with various examples from climate and ecosystem dynamics. Furthermore, we address the question to what extent such critical transitions can be anticipated based on early warning signals.
In addition, the dynamics of complex dynamical systems is often characterized by the different timescales on which certain processes act. This is particularly important for applications in climate science in the following situations: (a) different so-called tipping elements of the climate system possessing different intrinsic timescales influence each other or (b) climate change developing on a certain external timescale is impacting natural and/or man-made systems possessing a different intrinsic timescale. In the latter case, the systems become non-autonomous, a system class for which the development of a mathematical theory of critical transitions is still in its infancy. Such timescale separations strongly influence rate-induced and noise-induced critical transitions, but are also important for time-dependent shifting of basin boundaries in multistable systems [4].
Finally, we explain some mechanisms of the formation of extreme events from a dynamical systems point of view [5, 6].

References

[1] Schoenmakers et al., Chaos **31**, 053126 (2021).
[2] Vanselow et al., J. theor. Biol. **479**, 64-72 (2019).
[3] Halekotte et al., Sci. Rep. **10**, 11783 (2020).
[4] Feudel, Nonlin. Processes Geophys. **30**, 481-502 (2023).
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[6] Ansmann et al. Phys. Rev. E **88**, 052911 (2014), Phys. Rev. X **6**, 011030 (2016).

The basic concepts of the physics of complex systems illuminate questions of sustainability

<u>José Halloy</u>

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Questions of sustainability imply the need to take complex systems into account: from technical systems to the Earth system. Paradoxically, knowledge and approaches based on complex systems are still poorly represented in sustainability research. Here, I will consider the energy balance of the Earth system, arguing that we do not have an energy (J) problem, but fundamental questions concerning power (W) and materials. I will then focus on the questions raised by a long-term business-as-usual scenario. Are we heading for the end of metals? Next, we will examine the temporal dynamics of long-term deployment and maintenance of a technology, such as photovoltaics or nuclear power. We will also discuss the consequences of this dynamics in terms of material consumption. I will conclude by stressing the need to place the physics of complex systems at the heart of discussions on sustainability.

Dansgaard-Oeschger Events: Challenges of Predicting Abrupt Shifts in Multiscale Systems

B. Hobden[1], **P. Ashwin**[2] **and P. Ritchie**[3]
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The last glacial period (110-10 kya) was highly unstable, punctuated by millennial-scale climate oscillations termed Dansgaard-Oeschger (DO) events. A DO event is characterised by a rapid increase in temperature (10-16°C in high northern latitudes) over decadal timescales, followed by cooling over extended periods of centuries to millennia. Unlike the anthropogenic climate change we are experiencing today, DO events are quite unique. While the high northern latitudes rapidly warmed, there was simultaneous cooling over large portions of the Southern Hemisphere. Understanding how Earth's climate was able to undergo these natural 'tipping points' is crucial to gaining a greater knowledge of the stability of our current climate under the pressures of global warming. The precise cause of these abrupt shifts is still subject to debate. Building upon the low-dimensional model presented by Boers et al.[1], we present a stochastic nonlinear model that can induce self-sustaining oscillations through feedbacks between sea ice and the Atlantic Meridional Overturning Circulation. Here, transitions between stadial (cold) and interstadial (warm) states are a result of bifurcations in an underlying fast subsystem connected to sea ice extent. Changes in the subsurface water temperature in the North Atlantic modulate the duration spent in stadial conditions, with canard trajectories offering explanations for interesting behaviour for sustained stadial periods and smaller transitions that do not trigger full DO events. Our model, therefore, uses a combination of noise and bifurcation in a multiscale system and finds tipping in the fast subsystem. This approach suggests that if early warning signals are present, they may be hard to detect in the timescale of the slower subsystems.

References

[1] N. Boers, M. Ghil, D.D. Rousseau, Proceedings of the National Academy of Sciences of the United States of America **115**, 47 (2018)

Complexity of ice sheets - physical processes of the Greenland Ice Sheet

Angelika Humbert[1,2]

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2: University of Bremen, Department of Geosciences, Bremen, Germany

Ice sheet dynamics is gravity-driven lubricated flow, but numerous non-linear processes on many spatial and temporal scales make it a complex system. Polycrystalline ice in glaciers behaves as a viscoelastic material, with ice acting as a solid on short time scales and as a viscous, nonlinear fluid on long time scales. With temperatures ranging from pressure melting point to about -60°C from the base of the ice sheet to its surface, its viscosity varies over several orders of magnitude. In addition to the deformation of ice, sliding of glaciers and ice streams over the bedrock is another nonlinear process. The subglacial system is offering even more challenges with meltwater at the base of ice sheets forming a hydrological system and water pressure in that system affecting sliding velocity. We will discuss the Greenland Ice Sheet here primarily, because its extensive surface melting is the next level of complexity, as fast drainage of lakes facilitated by crack formation is perturbing the subglacial hydrological system nearly instantaneous. The presentation aims to stimulate discussions on modelling such complex systems adequately.

Broadening the scope of anthropogenic influence in extreme event attribution

A. Jézéquel[1,2]

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The science of extreme event attribution (EEA) goes back to Allen (2003), who introduced the idea of comparing the probability of occurrence of an observed event in the *factual world*, i.e., the world as we know it, to its probability in a *counterfactual world*, i.e., a world that could have been, in the absence of climate change. Since then, there has been a growing number of studies (Olsson et al, 2022) and EEA has been propelled as a novel way to communicate how climate change is already affecting the weather (Jézéquel et al 2020). One of the key current challenges for EEA is to not only attribute to human activities changes in extreme weather events but also in their impacts. Another challenge, more on the communication side, is that EEA may participate to the so-called “climatization” of natural disasters, i.e. that highlighting the role of climate change may also contribute to the invisibilisation of other factors leading to the observed disasters, such as maladaptation and mismanagement from the local authorities (Lahsen and Ribot, 2022).
In parallel, the disaster risk reduction (DRR) community has developed tools to evaluate how human societies affect exposure, vulnerability, and ultimately the impacts of extreme weather events, with less attention to the role of anthropogenic climate change. In this talk, I will argue that adapting current practice in EEA to also consider other causal factors would provide richer and more comprehensive insights into the causes of disaster impacts. To this end, I will present a framework for EEA that would generate a more complete picture of human influences on impacts and bridge the gap between the EEA and DRR communities.

References

[1] M.R. Allen, Liability for climate change. Nature **421**,891-892 (2003)
[2] Jézéquel, Aglaé, et al. "Singular extreme events and their attribution to climate change: A climate service–centered analysis." Weather, Climate, and Society **12.1**, 89-101 (2020)
[3] Olsson, Lennart, et al. "Ethics of probabilistic extreme event attribution in climate change science: A critique." Earth's Future **10.3**, e2021EF002258 (2022)
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Long range temporal dependence in atmospheric data

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It was Hurst who detected Long Range Temporal Dependence (LRC) in data of the river Nile. Meanwhile, thanks to Detrended Fluctuation Analysis DFA and its wavelet based counterpart, LRC has been observed in many data representing atmospheric or geophysical phenomena. Its presence causes the auto-correlation function of some signal to decay extremely slowly, most often as a power of the time lag. This has several important consequences for the analysis and understanding of such data. Due to the dependence of successive data points, the information contained in a finite sample is much less than that contained in an independent sample of identical size, giving rise to the notion of *effective sample size*. Due to strong correlations, the signal might appear to possess a trend even if it is stationary. In particular, extreme events and deviations from the mean appear as clusters, thereby sometimes pretending sudden changes in the behaviour of a system. We illustrate these issues using temperature series, precipitation series, and river levels. We demonstrate the adverse effects for the data based understanding of how climate change affects local observations and in particular the frequency of extreme weather events.

Utilizing long-memory and teleconnections for stochastic forecasts of winter temperature extremes

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Long memory (or long-range correlations) and teleconnections, i.e. long-lived atmospheric pressure patterns, are potential sources of subseasonal-to-seasonal predictions. Here, we infer a one-dimensional nonlinear stochastic model of daily temperature fluctuations which captures both long-range correlations as well as external driving by the Arctic Oscillation (AO) index. To this end, we employ a recently introduced method for reconstructing nonlinear long-range correlated stochastic models ([1]) which combines fractional calculus and stochastic difference equations. A causal analysis of AO and North-Atlantic Oscillation indices and European extreme temperatures reveals the largest influence of the AO index on daily extreme winter temperatures in southern Scandinavia. Binary temperature forecasts of the model for Visby Flygplats, Sweden, shows predictive power for up to 20 (12) days lead time for maximum (minimum) daily temperature (66% CI) while an AR(1) model possesses predictive power for only 8 (3) days lead time for daily maximum (minimum) temperature (66% CI). Our results show the potential of long memory and teleconnections for extreme temperature forecasts.

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From glaciers in Chamonix to the globe: quantifying the ice cost of our greenhouse gas emissions

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Glaciers exhibit a delayed response to climate change, meaning that the glacier retreat we observe today is a direct result of past greenhouse gas (GHG) emissions. Similarly, ice loss is expected to persist long after emissions have ceased. In this presentation, I will explore historical changes in the glaciers around Chamonix and discuss the implications of glacier change for local communities around the world. Following this, I will introduce new global glacier projections derived from an innovative model chain, establishing a direct connection between emission policies and the corresponding glacier response. Using these data, I will quantify the "ice cost" of our emissions — not in monetary terms, but in terms of how much glacier ice can (still) potentially be preserved.

Mountain glaciers are disappearing faster than ever observed. What are the remaining big questions in glaciology?

F. Maussion[1]

[1] *University of Bristol, Bristol, UK*

In this talk I will discuss the current certainties and uncertainties in future glacier change, and their consequences. I will illustrate how our knowledge about glacier change has considerably improved over the last decade, thanks to satellite data and new computational models. I will then focus on the major remaining uncertainties in our projections and discuss a few of the remaining "big questions" in glaciology and what might be needed to address them. These questions are particularly relevant to better inform adaptation needs in mountain regions..

Topological tipping in a low-order Atlantic Meridional Overturning Circulation model

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The Atlantic Meridional Overturning Circulation (AMOC) presents quasi-stationary states during interglacial intervals and chaotic variability during glacial intervals, associated with warm and cold climate states. Here, we use low-order deterministic models of the AMOC that mimic the main traits of the system's behavior (Sevellec and Fedorov, 2014; 2015). The first model only includes the chaotic variability of the interglacial interval, while the latter is subject to slow deterministic forcing to account for interglacial intervals as well. A change in the topological structure of a flow in phase space implies a major change in the non-autonomous dynamical system (or in any of its parts) that gave rise to those solutions. This work provides the first topological study of the flow in phase space associated with deterministic models of the AMOC. The solutions are studied using a new mathematical tool — the templex, introduced in Charó et al (2022) — and dissecting the phase-space into several identifiable components, connected at certain joints. A templex is a mathematical object composed by a cell complex and a directed graph in order to describe the topological structure itself and the non-equivalent pathways around the structure. The templex approach is based on the fact that the topological structure of a flow in state space is intimately related to the fundamental mechanisms that act to shape the evolution of a dynamical system. This enables identifying the types of processes captured by a model or observed in a time series in order to validate or compare them. The comparison between both models is done by building a templex directly from the solutions of both equation systems and by computing their topological properties. A change in the topological properties of the templex is indicative of a topological tipping point.

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Non-equilibrium thermodynamics of extreme events in wind turbulence and water waves

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Waves and turbulence are compared based on common multi-point statistics is presented. The complexity of both systems is described by special scale-dependent Fokker-Planck equations, which can be derived directly from empirical data. This stochastic description allows short time predictions and allows to define entropy values for all wave events and wind fluctuations. Negative entropy is associated with extreme events; moreover, the statistics of the entropy values follow the fluctuation theorems. Thus, negative, and positive entropy events therefore balance each other out, i.e. an extreme event is rigorously linked with normal fluctuation. Finally, the stochastic approach for these complex systems allows the definition of instantons, which we combine with entropy to entropons. All this enables also to determine rarest events, even those that are not measured. For waves, we find the "three sisters" as a very rare event.
Along with this presentation we also explain an open-source software package [3].

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Atmospherically-paced chaotic ocean variability: towards a dynamical system viewpoint.

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Mesoscale ocean turbulence is the best-known expression of Chaotic Intrinsic Variability (CIV), which spontaneously emerges from the unstable ocean circulation regardless of the atmospheric variability. Substantial amounts of CIV are also found up to the scale of basins and decades, potentially produced by large-scale baroclinic instability or resulting from spatiotemporal inverse cascade processes.

A 56-year atmospherically-forced 50-member 1/4° large ensemble simulation of the global eddying ocean/sea-ice system has been performed in the context of the OCCIPUT project to explore these phenomena using the NEMO model. We first show that the low-frequency large-scale (LFLS) CIV has climate-relevant imprints over most of the globe, is largest in western boundary currents and south of about 30°S, and competes with (and in certain zones exceeds) the atmospherically-forced ocean variability (AFV) in terms of amplitude.

However, the separability of AFV and CIV is questionable in the general case. Concepts from non-autonomous dynamical systems and information theories are leveraged to avoid this separation, and to probabilistically describe the ocean variability as an atmospherically-modulated oceanic "chaos". The partly random character of multi-scale ocean fluctuations in the eddying regime questions the attribution of observed signals to sole atmospheric drivers, the turbulent ocean predictability and its potential influence in high-resolution coupled simulations.

Effects of Delay Variations in Dynamical Systems

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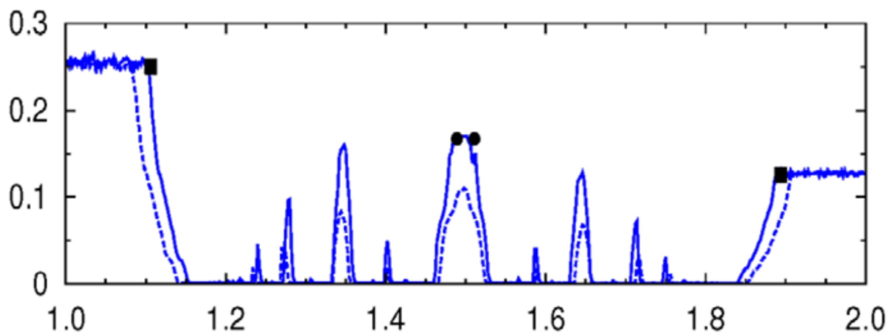
The future evolution of a dynamical system often depends not only on the current state, but also on states in the past. Well-known examples are found in very diverse fields, such as population dynamics, machining, nonlinear optics, life sciences, or climate dynamics. In modelling such systems, the associated delay times, for simplicity, are often assumed to be constant in time. Although it is clear that this is an idealization, its general consequences are not well understood. Only recently a systematic investigation of effects of time-dependent delays was started [1], which led to the discovery of new forms of chaotic behavior [2, 3]. It was also shown [4] that a smooth variation of delay parameters can lead to a wild variation of transport coefficients, as depicted in the figure:



It will be discussed with several examples under which circumstances such strong effects of non-constant delays can be expected. In addition, open problems and possibly rewarding directions of future research will be addressed.

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Millennial Chaotic Variability of the Atlantic Overturning Circulation in an Idealized Model

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A striking feature of paleoclimate records is the greater stability of the Holocene epoch relative to the preceding glacial interval, especially apparent in the North Atlantic region. In particular, strong irregular variability with an approximately 1,500-year period, known as the Dansgaard–Oeschger events, punctuates the last glaciation, but is absent during the interglacial. Prevailing theories, modeling and data suggest that these events, seen as abrupt warming episodes in Greenland ice cores and sea surface temperature records in the North Atlantic, are linked to reorganizations of the Atlantic Meridional Overturning Circulation (AMOC) between a an intense and a weak state. Here, we formulate a new low-order model, based on the Howard–Malkus loop representation of ocean circulation, capable of reproducing millennial variability and its chaotic dynamics realistically (Fig). It is shown that even in this chaotic model changes between intense and weak AMOC are predictable [1]. We then explore differences in the AMOC stability between glacial and interglacial intervals of the 100,000-year glacial cycle of the Late Pleistocene [2]. Previous studies show that the edge of sea ice in the North Atlantic shifts southward during glacial intervals, moving the AMOC southward. Here we demonstrate that such a southward displacement makes the system unstable, which explains chaotic millennial variability during the glacials and the persistence of stable ocean conditions during the interglacials.

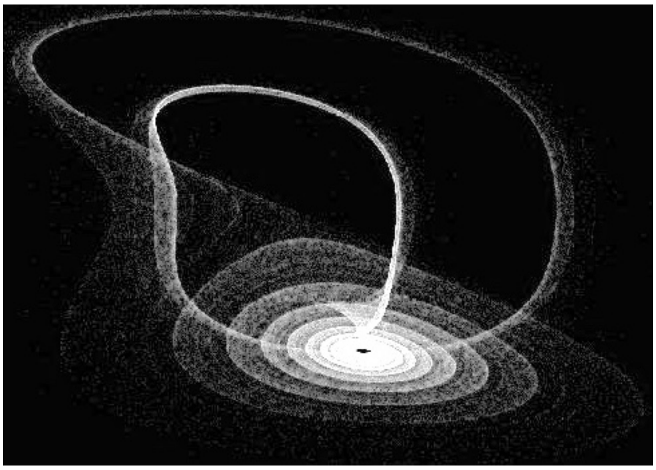

Fig: Attractor of the idealized model representing millennial variability of the AMOC. The attractor is computed through trajectory density in the phase space. The black and white colours are the normalized density. Black denotes the absence of trajectory in the region, whereas whiter colours represents denser region. 2×10^6 trajectories are used.

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The standard model of climate & what it's missing

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Few people appreciate what one might call the standard model of climate, the physics and principles upon which our understanding of climate change is based. Because few people understand the model, or are even aware that it exists as such, even fewer appreciate the assumptions upon which it based. In this talk I outline the this model, its assumptions, and the crises it is facing. Specifically I present evidence that climate change is associated with phenomena that the standard model cannot explain. I speculate as to the new physics beyond the standard model that will be necessary to explain these and future changes, and the research programme that will be required to uncover it.

Fluctuation-Responses and Tipping in Strongly Perturbed Nonlinear Systems

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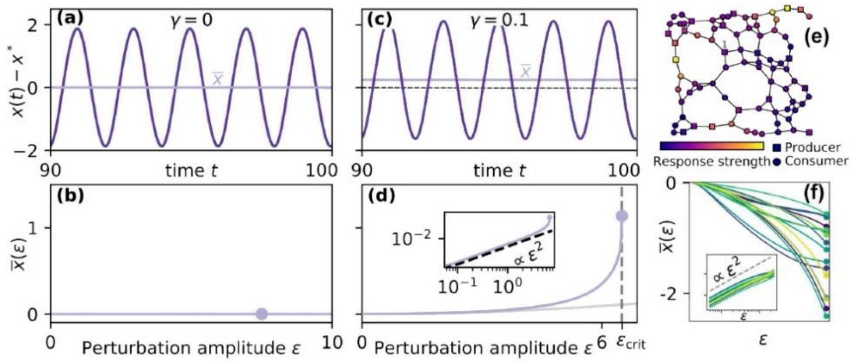

Figure 1 **Genuinely nonlinear system responses and tipping. a,b)** Due to symmetry, many classic model examples exhibit zero time-averaged shift $\bar{x}$ until first ceasing to respond only locally (solid disk in b), in accordance with linear response theory that predicts $\bar{x}(\varepsilon) = 0$. **c,d)** In contrast, responses of generic systems are **intrinsically nonlinear**, first quadratic in ε for small ε (light gray line) and increasingly deviating from it with larger ε. Tipping (solid disk in d)) emerges at **large** $\varepsilon_{\text{crit}}$. a)-d) show response dynamics of the overdamped pendulum model $\dot{x} = \gamma - \sin(x) + \varepsilon \sin(\pi t)$. Power grid models **(e)** with voltage variables x_n, $n \in \{1, \dots, N\}$ exhibit nonlinear responses **distributed across the network**, displayed in **(f)** for some sample nodes.

The collective nonlinear dynamics and reliable function of complex systems fundamentally underlie our daily lives, whether in biological cells, in power grids or in ecosystems. Many complex systems are strongly externally driven and may exhibit state tipping at large driving signals, yet state-of-the-art theoretical analysis methods have focused on linear responses suitable for weak driving signals. Here we report nonlinear responses emerging generically in driven nonlinear dynamical systems yet are absent from most text book examples. Moreover, at some critical (large) driving amplitude, responses cease to stay close to a given operating point and may diverge – the system tips. However, standard response theory fails to predict tipping amplitudes, even at arbitrarily high orders. We propose an integral self-consistency condition that captures the genuinely nonlinear response dynamics. and suggest to predict the tipping point by a large-perturbation expansion evaluated inside the self-consistency condition.

The novel approach may help to quantitatively predict intrinsically nonlinear response dynamics as well as bifurcations emerging at large driving amplitudes in non-autonomous dynamical systems. We illustrate our approach for a minimal one-dimensional model and capture the nonlinear shift of voltages in the response dynamics of AC power grid networks.

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A theory of randomness

Jin-Song von Storch

A common feature observed in many complex systems is that their solutions exhibit apparent randomness. Two approaches have often been employed to investigate random behaviors. The first involves stochastic models that incorporate a noise term or a Wiener process. While effective in generating different types of random behaviors for interpretative purposes, these models do not delve into the mechanisms responsible for the emergence of randomness. The second approach is rooted in dynamical systems theory, attributing random and unpredictable behaviors to uncertainty in initial conditions. This randomness — being arising from our inability to precisely identify the initial conditions — is external to the system. If randomness only emerges through external factors, solutions of a classical dynamical system should be purely deterministic.

We address this problem by considering a dynamical system governed by equations in form of $\mathrm{d}x/\mathrm{d}t = F(\mathbf{x}(t))$, where F is a deterministic nonlinear function of the full state vector $\mathbf{x}$ of the system and may contain external forcings. F describes interactions of component x of $\mathbf{x}$ with the other components of $\mathbf{x}$. The solution of such a system is generally non-periodic. Moreover, after integrating the system under constant external forcings for some time, the solution begins to vary stationarily. We refer non-periodic and stationary variations as equilibrium fluctuations.

Randomness in equilibrium fluctuations emerges from $G_T(t) = \int_t^{t+T} F\mathrm{d}t$, an integral of F over a time span of length T. We show that $G_T(t)$ can be expressed as $G_T(t) = c_T + d_T x(t) + f_T(t)$, composing of (apart from constant c_T) a dissipating component with strength d_T and a fluctuating component $f_T(t)$. The expression echos the idea behind the fluctuation-dissipation theorem that for a system in equilibrium, anything that generates fluctuations also damps the fluctuations. We show further that with increasing T, G_T undergoes a "metamorphose". After that, the dissipating component of $G_T(t)$ is transformed into the strongest possible dissipation with $d_T = -1$; the fluctuating component of $G_T(t)$, $f_T(t)$, is transformed into a white-noise-like forcing. The evolution of the solution of x from t to $t+T$, which follows $x(t+T) = x(t) + G_T(t)$, is then determined by $x(t+T) = c_T + f_T(t)$. Such an evolution appears to be random, since $x(t+T)$ is independent of $x(t)$; and cannot be reversed, since the past state $x(t)$ is canceled with the dissipation component of G_T. The properties of $G_T(t)$, currently undisclosed, introduce randomness and irreversibility as inherent attributes of dynamical systems subjected to constant external forcing conditions.

Ice matters:
The long-term legacy of short-term climate (in)action

Ricarda Winkelmann[1,2]

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From the mountain glaciers in the Alps to the ice sheets on Greenland and Antarctica – our planet is losing ice at a record rate. More than 28 trillion tonnes of ice was lost over the past two decades alone – to put this into perspective, one trillion tonnes corresponds to a cube of ice measuring 10x10x10 km^3, taller than Mount Everest. With unmitigated climate change, ice loss will accelerate further, leading to global sea-level rise well beyond the end of this century. What is more: as the land ice masses are increasingly getting out of balance, amplifying feedbacks might be triggered between ice, ocean and atmosphere, which can lead to substantial, widespread, and potentially abrupt or irreversible impacts.

In her presentation, Ricarda Winkelmann will talk about the dynamics underlying the recent observations and speed-up of ice loss from Greenland, Antarctica and mountain glaciers, as well as the implications for future sea-level rise. Due to the long response times of the land ice masses, policy decisions made in the next few years will have profound impacts on their future evolution, and hence on global climate, ecosystems and human societies – for this century and beyond.

Statistical challenges to model and simulate climate extremes

Pascal Yiou, LSCE

Extreme Event Attribution (EEA) is the corpus of statistical tools to determine how climate change affects the probability of occurrence of extremes. When record breaking events occur, one faces the difficulty of estimating such (low) probabilities, because of obvious sampling issues from observations. One way to overcome this difficulty is to design climate models and appropriate simulation protocols to sample such extremes. I will discuss how rare event algorithms can be applied to classes of climate models (from physical to stochastic models) to generate large ensembles of "unprecedented" extremes that are physically plausible. A stochastic weather generator will be designed to emulate those events. I will illustrate those models on concrete test cases.

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Abstracts of Posters

(in alphabetical order)

Deep Learning Methods Applied to All-Sky Cloud Coverage Estimation

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Measuring the level of cloud coverage (CC) is important when analysing the absorption of solar radiation, the cloud formation process, and also to improve the forecast in general. This is becoming a more common task with the availability of digital sensors and their usage in monitoring the sky. In this study we present a method of estimating the level of cloud coverage using Deep Learning (DL) applied to all-sky images of Meteorites Orbits Reconstruction by Optical Imaging (MOROI) network [1, 2]. To label the data, a supervised validation was employed on the daytime images captured during the course of two years, recorded on Galati, Romania These were divided into three groups; CC <20%, CC between 20-80%, and CC >80%. Next, a set of DL models were trained, optimized and tested towards accurately classifying images according to each group. We found that the classification accuracy can range between 89-95 % depending on how the cloud coverage is labeled and how the daytime is defined. This is mostly due to thin cirrus clouds, tricking the models, or poor sky illumination during sunrise or sunset. We discuss these methods and present a few strategies which circumvent classification problems, to further increase the accuracy of models. The next step is to extend the study on the rest of the network, and also combining it with other sensors (e.g. satellite data) in order to understand the cloud-circulation coupling and its impact across climate models.

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A generalized model for mutualism reveals the effect of network topology and size on the dynamical stability of mutualistic networks

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Mutualistic interaction networks, such as plant-pollinator or plant-seed disperser networks, are globally under pressure due to anthropogenic disturbances and global change. Thus, studying their response to perturbation is of high relevance.

The method of Generalized Modelling provides a powerful tool to investigate stabilizing properties of ecological networks, allowing efficient calculation of dynamical stability while using parameters with clear biological interpretation. We develop a generalized model for mutualism focusing on plant-pollinator interactions, including processes such as visitation, resource extraction and pollen delivery. Deriving our model from a consumer-resource model explicitly taking into account resource dynamics and pollinator competition for limited plant resources is a key ingredient of our model.

This model allows us to investigate the influence of network topology and size on dynamical stability in a realistic mutualistic model and study its relation to the strength and distribution of feedback loops.

How do mesoscale eddies evolve in time ? Numerical simulation accuracy compared to observations

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[2] *Laboratoire de Météorologie Dynamique, Palaiseau, France*
[3] *Laboratoire d'Océanographie Physique et Spatiale, Brest, France*

Mesoscale eddies are ubiquitous turbulent structures in the ocean. Most studies on the mesoscale use a composite approach, averaging eddies in time and space. Recently several studies developed a Lagrangian approach following individual eddies in time. This approach revealed a complex seasonal evolution at the mesoscale in both surface and subsurface signatures. The eddy-induced sea surface temperature (SST) anomaly shifts for anticyclones from warm-core in winter to cold-core in summer (and conversely for cyclones). In subsurface the mixed layer depth (MLD) deepens significantly in the core of the anticyclone in late winter compared to the outside.

The mesoscale seasonal evolution of a Mediterranean anticyclones is assessed here using in a high-resolution numerical model with realistic background stratification and fluxes. Our sensitivity analysis shows that the eddy SST anomaly can be accurately reproduced only if the vertical resolution is high enough (~4m in near surface) and if the atmospheric forcing contains high-frequency. In summer with this configuration, the vertical mixing parameterized by the k-ε closure scheme is 3 times higher inside the eddy than outside the eddy, and leads to an anticyclonic cold core SST anomaly. This differential mixing is explained by near-inertial waves ($\omega \sim f$), triggered by the high-frequency atmospheric forcing. Near-inertial waves propagate more energy inside the eddy because of the lower effective Coriolis parameter f in the anticyclone core. On the other hand, eddy MLD anomaly appears more sensitive to horizontal resolution, and requires SST retroaction on air-sea fluxes.

This is the first time that sub-inertial waves concentration in anticyclones is linked in a numerical study to an increased mixing in near surface, spontaneously retrieved through the k- ε mixing closure. This process highlights the need of both fine vertical resolution and atmospheric forcing at sufficiently high frequency to correctly reproduce mesoscale eddies evolution. At present stage, global operational models do not have the resolution to capture these phenomena. According to this study vertical grid step about 4m in the upper thermocline would then be necessary to accurately reproduce mesoscale temporal evolution.

Earth System surrogate models via Quality-Diversity optimization and Physics-Informed Neural Networks

L. Cazenille[1], N. Bredeche[2] and J. Halloy[1]

[1] Université Paris Cité, LIED, Paris, France
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Surrogate models, or emulators, approximate complete models of complex systems - making it easier and far less computationally expensive to explore their parameter spaces. Physics-Informed Neural Networks (PINNs) are a promising solution in this field, offering low computational costs and high fidelity even with little data: they take direct account of the physical principles of the system (differential equations). However, it remains difficult to train them to reproduce nonlinear and high-dimensional systems, such as Earth System Models (ESMs), as this makes the cost function noisy and deceptive. This is alleviated here by using Quality-Diversity algorithms, a recent family of optimisation methods capable of handling this type of problem without getting stuck in local optima, as is the case with classical training methods. We show preliminary results that validate our approach in modelling carbon-cycle ESMs models using PINNs. This methodological work is part of a wider effort to model the Earth's possible trajectories in the face of climate change, with the long-term aim of helping to anticipate and manage critical ecological tipping points.

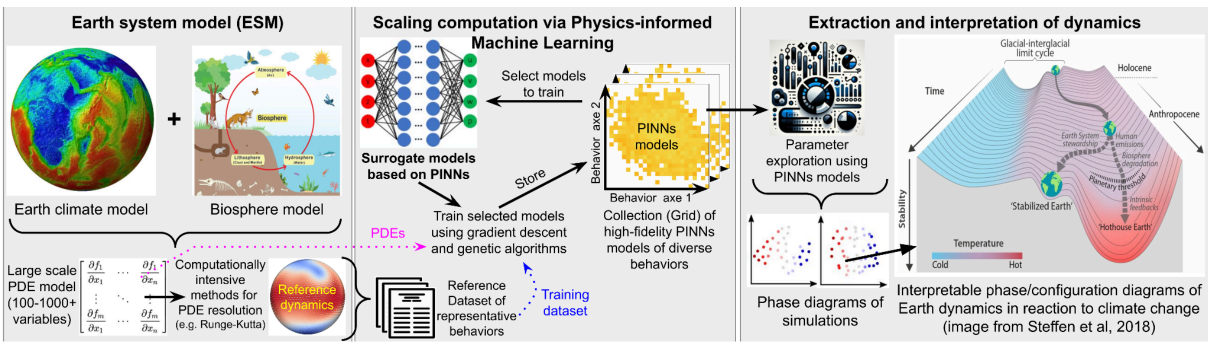

Figure 1: Workflow of the methodology presented in this project.

A single-species population model

<u>Misha Chai</u> and Holger Kantz

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There is a growing recognition that long-term or asymptotic behavior is rare and focusing on transients might be more effective approach to grasping the complexity of ecological systems. Especially super-long transients that can persist for a super-long period of time are key to understand species coexistence, biodiversity, and predicting regime shifts. Here based on the understanding of logistic map, we proposed a simple difference equation, where reveals complex dynamics, including super-long transients, regime shifts, and the coexistence of cyclic and chaotic behaviors within a single dynamical system.

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The increased likelihood of plankton community changes following marine heatwaves

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When modelling climatic systems, it is important to carefully assess the interaction between the many timescales, as certain changes in their interplay can affect the likelihood of observing critical transitions to distinct environmental regimes. Marine heatwaves weaken state-based resilience in plankton communities. The communities become more susceptible to noise-induced shifts in species' concentration levels following prolonged periods of increased temperatures. This is shown in a Truscott-Brindley model [1], a stochastic fast-slow system that encapsulates the interaction of phytoplankton and zooplankton during *red tide* events. Deterministically, the system is bistable, with stable states of high/low phytoplankton biomass; environmental perturbations to the (temperature-driven) species' growth rates are modelled using Ornstein-Uhlenbeck processes with correlation time parameter τ. During marine heatwaves, the correlation time τ will temporarily increase. With ensemble simulations of phytoplankton collapses, we assess how mean first-exit times from the basin of attraction scale as the noise strength weakens, across different prescribed values for τ. These scalings reveal the systems' quasipotential barrier heights, a concept of Freidlin-Wentzell theory [2] quantifying resistance to noise-induced escape from a domain. We observe a convex-type relation between the vulnerability to critical transitions and correlation time τ of the perturbations. Indeed, system resilience falls substantially as the noise becomes more correlated, across a physical parameter range for τ. This trend is also seen in the action values of most probable transition paths for escaping the basin of attraction, found using an augmented Lagrangian method [3] to overcome the degenerate noise structure. To dynamically explain these findings and assess their generality, we examine results from other studies on how climate tipping points, or stochastic escapes, depend on the correlation time of perturbations.

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Links between subtropical high-pressure systems and stratocumulus clouds variation

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Stratocumulus clouds contribute significantly to the global energy budget as they are the Earth's predominant cloud type and contribute strongly to Earth's albedo. They are known to predominate in the subtropics, especially on the eastern edge of the subtropical highs. Previous studies have confirmed the importance of these highs for stratocumulus clouds, but the variation relationship between highs and the cloudiness lacks investigation. Our study investigates this relation for both the annual cycle and deseasonalized time series for the five major subtropical high-pressure regions. It has been shown that the estimated cloud top entrainment index (ECTEI) is a useful predictor for the stratocumulus cloud fraction for both time scales. We show, however, that the variation of the highs provides additional information on the cloud fraction change on an annual cycle. The Northern Hemisphere is more sensitive to the highs change compared to the Southern Hemisphere. Variations in the structure, area, and location of subtropical highs are not considered the dominant influencing factors (correlates about 0.3). Nevertheless, we found a qualitative preference that stratocumulus clouds prefer a flatter, large, and westward subtropical high.

Delayed and transient impacts of the NAO on subdecadal variability of Norwegian Sea temperature

Abstract

It has been demonstrated that poleward ocean propagation plays a role in connecting salinity variability in the Nordic Seas with upstream variations in the North Atlantic subpolar gyre (SPG). It remains unclear why the impact of SPG variations on downstream temperature is limited. In this study, we disentangle the roles of the SPG and the North Atlantic Oscillation (NAO) in the subdecadal variability of Norwegian Sea temperature. With emphasis on the subdecadal time scale, we illustrate the delayed and transient impact of the NAO on Norwegian Sea temperature. By inducing SPG variations via buoyancy forcing, the delayed impact of the NAO manifests itself through the oceanic pathway. The resulting temperature anomalies in the SPG region show clear poleward propagation to the Norwegian Sea in the following 4 years. Besides, the NAO exerts a transient impact on the Norwegian Sea temperature by modulating wind-driven transport into the Norwegian Sea. The positive NAO phase elevates sea surface height along-shelf, enhancing temperature transport into the Norwegian Sea simultaneously and vice versa. With the direct influence and oceanic pathway, the twofold impact of the NAO reveals insights into the low predictability of Norwegian Sea temperature. Although that lagged impact stores subdecadal memory of the subsurface ocean, the transient impact via wind-driven transport and heat flux may counteract the lagged oceanic signal thus degrade prediction. We further show that Norwegian Sea temperature is better predicted at forecast lead year 1 when the NAO is initialized in the positive phase, highlighting the limited predictability provided by NAO and challenges in predicting Norwegian Sea temperature.

Interplay of structure and randomness in complex ecological communities

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Two distinct facets of many-species ecological communities have drawn significant attention from theory: complex networks of interactions, and robust macroecological patterns in species abundances and dynamics. Determining if species interactions, and which features thereof, are responsible for these patterns is an ongoing challenge for ecological theory. A growing body of ‘disordered systems’ theory investigates minimal models with random interactions, where broad statistics suffice to predict dynamical outcomes. However, interaction networks commonly possess large-scale structures, such as hierarchies or functional groups, that have also been used to explain community-level patterns. Here, we ask which results from random interaction models can be expected to be fragile or robust to the presence of such large-scale structures. We consider a simple superposition of structured and random interactions in a classic population dynamics model, and study its impact on macroscopic observables, abundance distributions and dynamical regimes. For equilibrium properties, randomness and structure combine in a surprisingly yet deceptively straightforward way: the studied patterns can almost be partitioned into contributions from each of these two components. On the other hand, non-trivial effects appear at the dynamical level: we find a generic mechanism through which randomness can stabilize the dynamical fluctuations that would have arisen from fully structured interactions.

Capturing intrinsic noise in the stochastic dynamics of discrete populations on networks

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In the regime of large intrinsic noise, where the numbers of individuals in populations interacting via a given network are small, the stochastic time traces of the system exhibit large fluctuations on the order of the mean of the process. This scenario can occur, for example, in small ecological populations or molecules reacting in a chemical reaction network, such as a gene regulation network[1]. Expensive stochastic simulations are usually employed in this regime to calculate the time-dependent observables[2]. We present a method[3] that captures the intrinsic fluctuations using self-consistently determined memory, which emerges from a perturbative treatment of the effective action of the Doi-Peliti field theory for the underlying discrete stochastic process. We demonstrate this method and its accuracy on single and multi-species binary reactions across a range of reaction constant values. Such an approach can also form the basis for a likelihood inference scheme from the fluctuating stochastic time traces.

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Sensitivity Analysis of the Lorentz Energy Cycle in the ICON-O Model

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This study provides an analysis of the ocean Lorentz Energy Cycle (LEC) simulated with an ICON-O configuration of 5km horizontal resolution. We focus on those aspects of the LEC related to the dissipation of mesoscale eddy energy. Since most processes relevant for eddy dissipation cannot be resolved even with 5km horizontal resolution, parameterizations are required to dissipate the energy. Typical parameterizations used in ocean models are bottom friction, vertical viscous dissipation and horizontal biharmonic dissipation. We analyse how these parameterizations are responsible for the simulated eddy energy dissipation. Dedicated sensitivity experiments estimate uncertainties arising from these parameterizations when typical friction parameters are modified. These experiments allow to assess the impact on the overall energy balance. Furthermore, we discuss how inertial and sub-inertial motions influence the overall energy dissipation. Overall, this study aims to provide the basis for future more realistic diagnostics and parameterizations of the processes involved in eddy dissipation.

Variability of the Arctic summer sea ice border on its way up North

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Every year, the area of the Arctic sea ice decreases in the boreal spring and summer and reaches its yearly minimum in the early autumn. Due to global warming, Arctic summer sea ice will most probably disappear.
It is still debated wheter this will happen abruptly and if early warning signals (EWS) for this disappearance can be found. Applying classical EWS based on critical slowing down, which only capture temporal changes, have not yielded significant results so far.
As the Arctic ice cover decreases, its border is retreating northwards towards the central Arctic. This retreat is not uniform and the variability of the sea ice edge over both space and time may yield an alternative EWS for the upcoming summer sea ice loss. Here, we track said border in observational and modelled data to study its variability as Arctic summer sea ice approaches its disappearance.

The origin of the observed global temperature extremes in 2023

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The year 2023 has seen a range of records and extremes: being the warmest year on Earth since 1850, the annual global temperature was estimated as 1.54 $\pm$ 0.06°C [1] with September 2023 exceeding any previous September by a margin of 0.5°C, which is an extremely rare event in the latest generation of climate model ensembles [2]. Regionally, notable extremes were seen in the North Atlantic sea-surface temperature and a record low extent of the Antarctic sea ice [3].
Recent variations in external forcings on top of anthropogenic warming include an increase of atmospheric water vapour due to the Hunga Tonga eruption in 2022, the reduction of marine aerosols and the variation in the solar cycle. However, these are not significant enough to explain the observed margin of either the annual global or the regional or monthly temperature extremes [1], [2]. The transition from La Niña to a moderate El Niño contributed to an increase in temperature on land and ocean but does not explain the observed spatial patterns or intensities. This suggests the importance of other modes of natural variability, especially for the September temperature anomaly. We thus aim to identify the roles of external factors and natural variability in the observed extremes and see them in the wider context of future climate change.

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Dynamics of the center of wind pressure: From large-scale turbulent structures to loads on a wind turbine.

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A stochastic method for the reconstruction of loads at the main shaft of a wind turbine (WT) is presented. The center of wind pressure (*CoWP*) was introduced by Schubert et al.[1]. This feature correlates large-scale turbulent structures of the wind with bending moments (T) at the main shaft the WT. Extensively, we reconstruct time series of such bending moments based on the characterization of the dynamics of *CoWP*. The Langevin approach [2] is used as a method for both, the characterization of *CoWP* and the reconstruction of T. Since *CoWP* is calculated purely from the wind field, this method allows a fast and computationally cheap procedure to characterize large-scale structures of the incoming wind, as well as for generating synthetic data for load assessment on the main shaft of the WT.

Figure 1(left) shows the correlation between the *CoWP* and the BEM-simulated bending moment (T_{BEM}). Figure 1(right) shows the agreement on the statistics between T_BEM and the stochastically reconstructed signal (T_r).

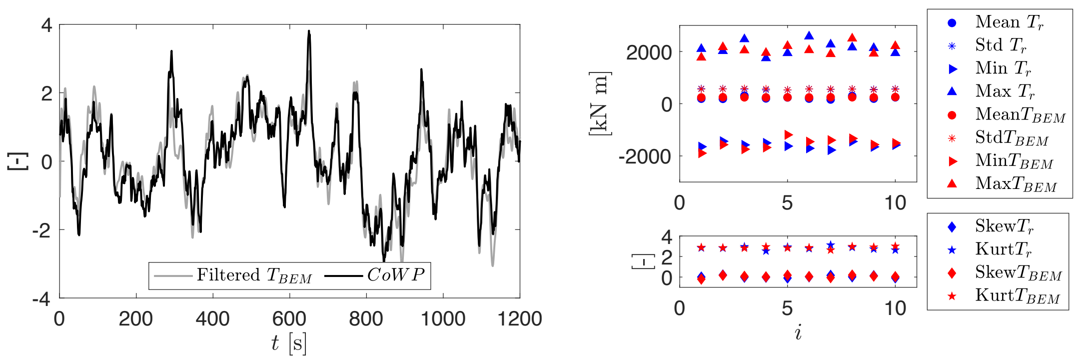

Figure 1. Left: Time series of CoWP, T_{BEM} and T_r. Right: Statistical characteristics of T_{BEM} and T_r.

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Anticipating critical transitions in multi-dimensional systems driven by time- and state-dependent noise

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Some high-dimensional complex systems of multiple time scales can be represented as low-dimensional dynamical systems under the influence of noise. In this framework, abrupt transitions induced by changes in model parameters may be understood as the result of bifurcations. When approaching a one-parameter bifurcation, the feedbacks that stabilise the initial state weaken and eventually vanish; a process referred to as critical slowing down (CSD). This motivates the use of variance and lag-1 auto-correlation as indicators of CSD in order to anticipate bifurcation-induced critical transitions. Both indicators require a prior dimension reduction to a one-dimensional time series. The use of variance is further limited to time- and state-independent driving noise, strongly constraining its generality. Here, we propose a data-driven approach based on deriving a multi-dimensional Langevin equation to detect local stability changes and anticipate bifurcation-induced transitions in systems with generally time- and state-dependent noise. Our approach substantially generalizes the conditions underlying existing early warning indicators, which we showcase in the example of a two-dimensional predator-prey model. This reduces the risk of false and missed alarms significantly and allows for a more holistic understanding of the low-dimensional system as well as the original high-dimensional complex system.

Enstrophy conditioned extreme-event statistics and their morphology

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A key problem in our understanding of turbulence is the existence of the so-called dissipative anomaly [1][3]. One possible explanation to this could be the existence of quasi-singularities (or extreme-events) in the flow, which are able to dissipate energy inertially, near or below the Kolmogrov scale [1]. However, to date, there is no experimental demonstration of this phenomenon, nor any proof of its link with singularities or quasi-singularities.
This work aims to help fill this void with state-of-the-art experimental results from the Giant-von Karman (GvK) facility at CEA Paris-Saclay. [2]. The resulting data covers a range of Reynolds number (6,000-150,000) at resolved scales rarely reached in experimental flows (down to ¼ Kolmogorov). By performing 4D Particle Tracking Velocimetry at these very high spatial resolutions, the time-resolved velocity fields are used to better understand the occurrence of extreme events in turbulence, both statistically and instantaneously.
We statistically investigate the amplification of vorticity gradients occurring during intermittent extreme events. By conditioning these statistics using enstrophy, we allow for a better understanding of the vortex stretching mechanisms specifically in those regions where intermittency occurs, and exclude quiescent regions. [4]. Additionally, we re-investigate the possible universality of the alignment of vorticity vector with the intermediate strain-rate eigenvector [5]. This work also investigates individual extreme-event morphologies to better understand amplification processes in such events. The identification of an event in time and space allows for the tracking of this event spatio-temporally

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Varieties of Democracy in Times of Global Change: The V-DEM Dataset, Dynamics of Democracies, and Impact of Global Events

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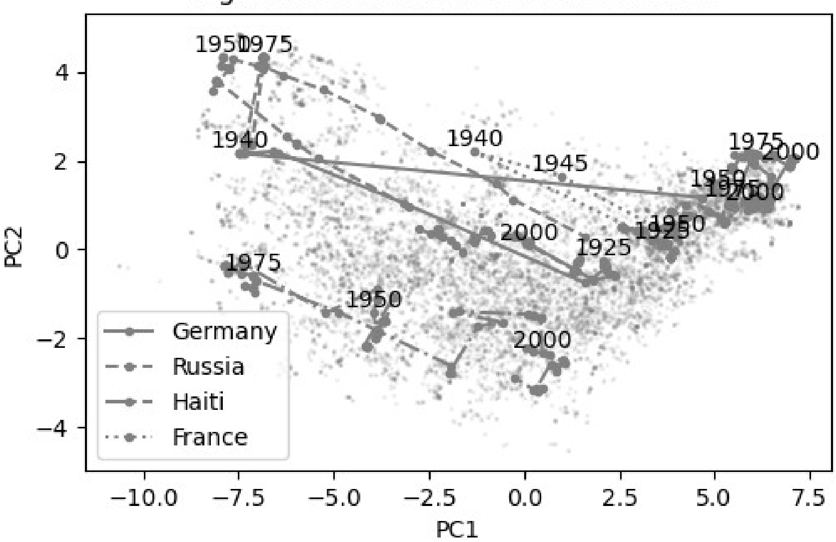
In my contribution, I want to focus on the empiric characterization of political regime types, their dynamics, interactions, and correlations. This is work in progress: I aim to outline the cornerstones of my Bachelor's thesis rather than present my own results.

V-DEM is an international project headed by the V-DEM institute at Gothenburg, Sweden. Its goal is to gain sophisticated insights into commonalities and differences of various regime types. To this end, the project gathers regional experts and a plethora of opinions, classifying countries in time using sharply defined indicators[1].

Fig. 1: Evolution of selected countries



By principal component analysis, one can greatly reduce the dimensionality of this dataset, in particular the 24 indicators comprising the electoral democracy index (EDI). Indeed, the first component reproduces the EDI. PC2, however, seems to indicate the balance between the regularity of elections (positive) and freedom of expression/ association (negative)[2].

This yields a two-dimensional representation of a country's political state. In particular, we can trace specific countries and look for correlations with known events. Fig. 1 depicts some exemplary trajectories. Clearly, we can identify the impact of world war two on both Germany and France as well as the Soviet Union's transition towards a more democratic regime and back to a slightly more authoritarian state (Russia). Haiti, however, seems to be trapped in a rather disordered state.

This leads to a number of questions: Which countries interact and how to quantify this? How to quantify changes in trajectories, indicating major events? Could there be general principles of motion or chaotic regions? In my thesis, I aim to apply methods of extreme value statistics and nonlinear dynamics to gain some further insights.

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Modelling dynamics of political regime types in the 20th century

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Can the evolution of political systems be predictable? Is there a way to define their state with a maximum of two state variables?
To answer these questions we are analysing part of the V-Dem Research Project dataset, the world's most detailed democracy ratings. It consists of hundreds of indicators quantifying different aspects that define the democracy level of more than 170 countries, which reveals the complexity of political systems and their definition. [1]
We apply the dimensionality reduction method called diffusion map and identify a two dimensional manifold containing all data points corresponding to all countries and years available, between 1900 and 2021. Being the first coordinate strongly aligned to the Electoral Democracy Index (EDI), this novel representation distinguishes autocracies from democracies in a surprisingly clear way. We also identify regions in the manifold that are related to specific regime types and additionally, suffrage types. By fitting a Gaussian Mixture model to the temporal evolution, we detect the collective response of the system to historical events. Based on our results, we suggest a predictive model for the evolution of political systems.

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Characterising Edge States: Measures on chaotic non-attracting invariant sets

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In this work, we define an invariant probability measure on chaotic non-attracting invariant sets that is both useful from a practical point of view and has desired theoretical properties. Building on Sweet and Ott (2000), we formalize their ideas by defining a measure via the ratio of the Lebesgue measures of two sets and show how to sample it numerically. Properties of a similar measure on the stable and unstable set of the invariant set are derived as well. We discuss the measures' and the sampling techniques' relevance for simple low dimensional models as well as their usefulness and limitations for more complex and higher dimensional models. Knowledge about this measure on a non-attracting set (e.g. on a saddle or on an edge state) provides information about its fractal dimension and, in the case of an edge state, about the geometric complexity of the basin boundary. This can be useful to better understand (climate) tipping phenomena, uncertainty close to a basin boundary, and the dynamics of potentially long-lived chaotic transients.

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Where is the error?
Self-organization and unsupervised learning in neural networks through dendritic error computation

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Neural networks are truly complex systems. They consist of thousands of neurons that are strongly cross-linked and influence each other through the emission of discrete electrical pulses, so called spikes. It is an open challenge how neural networks can use dynamic rewiring to enable stability and functionality despite the complex dynamics that emerge through the highly recurrent and delayed coupling between the cells.

One particular challenge is how neurons can find an efficient representation of sensory inputs by, on the one hand, detecting correlated patterns in their inputs, and, on the other hand, reducing redundancies with other neurons so that each neuron specializes on a distinct input pattern [1].

Here, we show that spiking neurons can find such efficient sensory representations through inhibitory feedback and a dynamic rewiring mechanism [2]. In particular, this rewiring mechanism is based on biologically plausible synaptic plasticity and an error signal that neurons can compute locally with the membrane dynamics at their dendrites.

This plasticity scheme shows a striking agreement with empirical evidence and overcomes previous challenges of implementing a broad class of unsupervised learning algorithms under the umbrella of predictive [4] and sparse coding [5] using spiking neurons [3]. We also demonstrate that it solves a major open problem of previous unsupervised learning schemes based on Hebbian learning that emerges in the presence of delayed feedback between neurons [2].

Our work provides a new perspective on self-organization in neural networks that stresses the role of inhibitory feedback and local membrane dynamics to orchestrate neural activity and rewiring.

More broadly, this work provides insights for the design of control mechanisms for complex systems, where error signals could help to better split the tasks among agents to overcome issues of delayed feedback and undesired synchronization.

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State estimation of urban air pollution with statistical, physical, and super-learning graph models

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We consider the problem of real-time reconstruction of urban air pollution maps. The task is challenging due to the heterogeneous sources of available data, the scarcity of direct measurements, the presence of noise, and the large surfaces that need to be considered. In this work, we introduce different reconstruction methods based on posing the problem on city graphs. Our strategies can be classified as fully data-driven, physics-driven, or hybrid, and we combine them with super-learning models. The performance of the methods is tested in the case of the inner city of Paris, France [1].

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Detecting the local and global variations of the long-range dependence in daily temperature data

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Detecting and understanding temporal correlations within climate systems provide both physical and practical interest. For instance, investigations of temporal correlations in the daily temperature can help understand global warming. Here we focus on the daily temperature data from ERA5 which is the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis of the global climate. We consider the time series of deviations of the daily temperature from their mean after removal of the annual cycle. The series of such deviations have been previously shown to exhibit both short and long range correlations. Employing the time-averaged mean-squared displacement (TAMSD) and detrended fluctuation analysis, we quantify the long-range dependencies via estimates of the Hurst index. We discover that the data exhibits global geographic-latitude dependent long range correlations. We further detect local variations in the Hurst index strongly dependent on the geographic location. The one-step deviations estimated from the TAMSD supports the conclusions obtained from the estimates of the Hurst index. Our results thus provide important practical insights into the trends in daily temperature.

Fluctuation-Responses and Tipping in Strongly Peturbed Systems

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Most network dynamical systems are out of equilibrium and externally driven by fluctuations. Linear and higher order perturbation theories capture the response dynamics to such fluctuations for small driving amplitudes. The larger the driving amplitude the more non-linear effects arise up to critical perturbation strengths beyond which the system diverges, i.e., tipping occurs. Standard response theories, providing answers in terms of polynomials, which are defined for arbitrarily large values, fail to capture such tipping in all orders. We propose an integral-self-consistency relationship to overcome these limitations and apply it to two models: a one-dimensional toy-model for exemplification and a power grid model, including active voltage dynamics. Our approach may help to quantitatively predict intrinsically nonlinear response dynamics, as well as bifurcations emerging at large driving amplitudes in non-autonomous dynamical systems.

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Non-equilibrium spectral correction in SQG turbulence

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Surface quasi-geostrophic (SQG) turbulence offers a simplified yet insightful model for understanding oceanic and atmospheric flows [1—3], crucial for climate modeling and weather prediction. Our study focuses on non-equilibrium (subleading) corrections to the inviscid invariant very often named as generalized enstrophy, in which, dimensional prediction shows the same -5/3 slope as in 3D turbulence. Our computations are generalized to a broader range of turbulent models, named as alpha-turbulence, where the SQG dynamics is inserted. We validate our findings through detailed analysis of well-resolved pseudospectral simulations and discussing the connection between intermittency and the influence of large, smooth structures on flow dynamics and statistics.

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Stochastic analysis of jump noise along with Langevin noise in real-world data sets

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The abstract should be headed by a **title**, **name(s) and complete address(es) of the author(s).** Please underline the name of the author who will present the paper and leave a 3.0 cm margin on top and 2.5 cm margin on all other sides. As font you should use Arial or Helvetica, 12pt with a line spacing of 16pt. The abstract can contain Figures, Tables and References, but the length of the abstract should not exceed **one** DIN A4 page. Please note that coloured abstracts will be converted to black-and-white.

Analysis and modeling of real-world systems by Langevin-type stochastic differential equations (SDE) has proven to be powerful for many applications. However, many systems are driven not only by a strictly normal-distributed, delta-correlated Langevin noise, but additionally show deviating noise properties. In many cases those systems can be better described by including a jump noise term in the SDE, accounting for non-Gaussian noise characteristics. We demonstrate the methodology at field data examples of snow hardness [1] and wind energy systems [2] where the inclusion of jump noise leads to improved results and additional insights.

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Langevin analysis of wind turbine control parameters

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Climate change is one of the big challenges of our time and wind turbines are a key technology for a low-emission power generation in the future. Being subject to turbulent inflow, the effective wind speed that encounters a wind turbine rotor can change by hundreds of kW within a few seconds [1]. These extreme events are transmitted to the generated power of wind turbines and therefore impair grid stability. In order to tackle this challenge, we aim to reduce strong fluctuations of the produced power, using the rotational energy of one or multiple wind turbines as a short-term source of energy. For this purpose, we choose a Langevin equation to describe the dynamics of wind turbine power conversion. This model can not only capture the dynamics on the necessary time scale of seconds, but is also a useful simplification of the complex power conversion dynamics due to the turbulent inflow. A drift term in the Langevin equation describes the deterministic part of the power dynamics and the fixed points of the drift map in phase space give the stable points of operation of the turbine. In contrast, a diffusion term accounts for the noisy part of the dynamics and captures all random contributions influencing the conversion process. The model was first applied to a wind turbine by describing the dynamics of the produced electrical power, conditioned on the inflow wind speed [2]. Using a non-parametric Nadaraya-Watson estimator, the coefficients quantifying both terms are estimated from temporally highly resolved synthetic field data of a wind turbine.
In order to temporarily use the rotational energy of a turbine, the rotational speed of a wind turbine is controlled by changing the torque on the electrical generator.
We therefore extend the Langevin description to the channels of generator torque and rotational frequency of a turbine. From the resulting drift field, we hope to obtain information about the expected gain in rotational energy and potential stability issues at different points in phase space. As a first result, we find that this drift field is physically reasonable and contains stable fixed points that match well with the fixed points of the electrical power dynamics. In the future, we may then use the drift field to dynamically adapt the generator torque, in order to efficiently rule out power peaks.

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Variational Integrators for Stochastic Hamiltonian Systems on Lie Groups

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Numerical methods for weather forecast have a long and rich history. Until recently, the main efforts were concentrated on the inclusion of more complex and accurate physical processes in the numerical models of atmospheric motion. As a minimum requirement, the framework of the introduction of noise should preserve the fundamental mathematical structure of the deterministic model. The geometric mechanics approach which we take here is designed to preserve the fundamental structure of fluid dynamics. In addition, major improvements could also be obtained by imposing that the numerics of the underlying geophysical fluid model part preserves the geometric structure and conservation laws of the continuous model. An efficient way to construct such numerical schemes for a large collection of fluid models from a unified point of view is to appeal to variational discretization.

This project exploits two major advances made recently in the area of geophysical fluid dynamics: stochastic geometric models and variational numerical integrators. In the first step we derive a variational integrator for stochastic Hamiltonian systems on Lie groups by using a discrete version of the stochastic phase space principle. The structure preserving properties of the resulting scheme, such as its symplecticity and preservation of coadjoint orbits are given, as well as a discrete Noether theorem associated to subgroup symmetries. Preliminary numerical illustrations are provided.

In the future, the benefits of the structure preserving properties of the newly proposed stochastic geometric integrators will be evaluated for instance with uncertainty quantification tests of the velocity decomposition by comparing solutions of the resulting stochastic partial differential equation with solutions of the deterministic fluid partial differential equation, computed on a refined grid. The geometry preserving integrators for stochastic geophysical fluid models will have the prospects to be used in weather, oceanic flows and climate simulations.

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Abstract

WE-Heraeus-Seminar

Title: Impact of Amazon Deforestation on Precipitation in a Strom-resolving Global Climate Model
Name: Arim Yoon

Complete deforestation of the Amazon basin is expected to lead to a significant reduction in Amazon rainfall, even to a threshold known as the tipping point. However, the results were supported by modeling studies that had the disadvantage of relying on a convective parameterisation and/or prescribed large-scale circulations. These limitations are sources of uncertainty because the parameterised model is too sensitive to changes in evapotranspiration that are expected to lead to a large reduction in precipitation, and the prescribed large-scale circulation can't account for the large-scale circulation feedback. To overcome these limitations, we simulate, for the first time, a scenario of complete deforestation of the Amazon without convective parameterisation and allowing for large-scale interactions. We find no significant reduction in mean annual precipitation and contrasting spatial patterns of precipitation change compared to previous studies. Both dry and wet seasons show increased precipitation over the core region of the rain belt, resulting in a north-south dipole pattern. The dipole pattern is explained by changes in the 700 hPa circulations, not by surface advection which is suggested by previous modeling studies. Our study shows that simulating the response of precipitation over the Amazon to deforestation requires simulating the feedback between precipitation and local processes, including evapotranspiration, surface moisture advection, and large-scale moisture convergence in the lower atmosphere. This is only possible with global km-scale climate models. Our study shows that missing basic physical processes can bias the response of precipitation to land surface changes.

Denoising and debiasing of complex real-world networks

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Complex real-world networks, modeling phenomena from protein-protein interactions [1] to climate change [2], are powerful distillations of reality that often reveal profound insights. However, studies of real-world networks often suffer from noise and bias inherent in the data collection process. The effort to mitigate such noise and bias almost always takes the form of link prediction, where traditional similarity-based approaches prove inadequate in practical applications, yet state-of-the-art approaches operate under specific assumptions that restrict their generalization ability [3,4]. Inspired by the maximum entropy framework and the generalized Wiener filter, we propose a network denoising and debiasing method that can be tailored to networks of different natures, with the hyperparameter tuning process done in an interpretable manner that leverages domain knowledge. We demonstrate solid mathematical motivation and promising experimental performance of this method.

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