K125171

Ensemble approach in climate dynamics and nonequilibrium processes

Final Report

Introduction

Prior to this project, both climate science and dynamical systems theory were aware of the ensemble approach, but mainly as a curiosity. Now, based partially on the view spread by the project and some of its results, the ensemble approach has become widely accepted in both disciplines. Researchers turned to realize that in systems with changing parameters a single time series is not representative of the dynamics either in experiments or in simulations due to the typical chaotic features of the dynamics, exhibiting a phenomenon referred to as the butterfly effect. Chaos implies that many different time evolutions are permitted by the equations of motion, thus, a faithful description can only be obtained if an ensemble of these permitted histories is studied.

The main research topics of the project, along with some of the key results, are given here with the intention of being understandable for non-experts (just like the text of the short summary):

i **Changing climate:** In addressing problems related to a changing climate, our main focus was on so-called teleconnections. These are curious statistical correlations in the weather of geographically remote regions. In a physically well-founded approach for utilizing ensembles of climate simulations, we identified in projections of the future climate an increasing teleconnection strength between the El Niño phenomenon and the precipitation over India in the monsoon season. By tracking ensembles of particles we showed that the prediction of pollutant clouds might become more difficult in a changing climate.

ii **Climate-motivated laboratory experiments:** Certain basic features of large-scale flow phenomena in Earth's climate system can be modeled using tabletop-size laboratory experiments. Our results revealed universal features in various processes ranging from temperature fluctuations in the mid-latitude atmosphere, through the robust reorganization of continents and oceanic currents 34 million years ago which triggered the glaciation of Antarctica, to certain general, defining properties of vortices in fluids and the atmosphere.

iii **General physical systems under parameter drift:** General physical systems are typically chaotic, and climate change motivates the study of systems subjected to parameter drift, systems representing nonequilibrium processes. The standard tools for identifying chaos are not applicable in such cases, and we developed new and robust ensemble-based tools to characterize chaos in these systems. Besides geometrical considerations, we proposed the application of a generalization of the Lyapunov exponent, the most important measure of the butterfly effect. The method can be applied in a wide range of physical problems as well.

iv **"Extreme" and "noisy" behavior in the above systems:** Better understanding the general underlying properties of the expected extremities in partly noise-driven long-range correlated complex systems (similar to Earth's climate) is of paramount importance for the mitigation of natural hazards. Our research explored the extreme "tails" of solar irradiance and wind speed distribution over large, continent-scale domains, the energy distribution of ocean eddies in the Pacific, and extreme temperature fluctuations in models of the mid-latitude atmospheric circulation.

A detailed and more specialized description of the results is given in Sections i-iv below, echoing in their titles the major research questions formulated at the beginning of the project.

Technical remark: as the research was ongoing up to the closing date of the project, we mention in this report yet unpublished results, but only those that are summarized in manuscripts close to submission to international journals. These latter manuscripts we refer to as preprint, 2023 in the list of publications.

(i) The proper establishment of evaluating teleconnections in a changing climate

The overarching feature of our teleconnection-related investigations is that statistical quantifiers have been evaluated with respect to an ensemble of climate simulations (instead of time in single climate simulations) such that the ensemble has been taken care of to have converged to a time-dependent dynamical attractor (a snapshot attractor). In a series of case studies, we have evaluated ensemble-based correlation coefficients (E-r) and introduced ensemble-based (snapshot) empirical orthogonal functions (snapshot EOFs, SEOFs), ensemble-based (snapshot) maximum covariance analysis and ensemble-based (snapshot) canonical correlation analysis. Relying on such tools, we have come to conclusions with high practical relevance in several concrete research questions, which we detail below.

We investigated the teleconnection between the El Niño–Southern Oscillation (ENSO) and the Indian summer monsoon (IM) using ensembles of climate simulations [Max Planck Institute Grand Ensemble (MPI-GE); Community Earth System Model Large Ensemble (CESM1-LE)] that encompass the 20th and the 21st century. We first considered E-r between classical ENSO indices and the all-India summer monsoon rainfall in the MPI-GE. Details in detectable trends in E-r are sensitive to the choice of the physical variable, the region of evaluation, the time period of the year, and the delay between the two phenomena. However, the teleconnection strength was found to *increase* on the long term in all cases. Existing literature, based on correlation coefficients evaluated over time (T-r) in instrumental records, discusses a *weakening* in the late 20th century. This discrepancy highlights that either T-r had given a misleading indication or the MPI-GE does not represent the Earth system faithfully. Either conclusion has serious implications regarding the (lack of) credibility of many studies, as T-r is still the main tool for the assessment of teleconnections and their changes, and the MPI-GE is widely used for preparing climate projections [1].

We also considered dominant spatial modes in the sense of SEOF analysis, snapshot maximal covariance analysis and snapshot canonical correlation analysis. We found that the strengthening of the ENSO-IM teleconnection is robustly featured in view of various representations. It turned out to be associated dominantly with the principal mode of ENSO variability. We have also shown that the forced change of the teleconnection is typically nonlinear. The test statistic utilized for this purpose captures a deviation from ergodicity regarding the correlation coefficient. We provided global maps of the test statistic (a degree of nonlinearity of the forced change) for the teleconnection between local precipitation and ENSO as well [2].

The changes in ENSO and its precipitation-related teleconnections were investigated in the CESM1-LE from 1950 to 2100 in terms of the leading SEOF of sea surface temperature (SST) variability. As illustrated in Fig. 1, the largest changes of the ENSO pattern occur in June–July–August–September (JJAS) in the central and the western Pacific, exhibiting a prominent increase in its amplitude; however, the increase is also considerable along the Equator in December–January–February (DJF). Importantly, the ensemble-based Niño3 amplitude also shows an increase of about 20 % in JJAS and 10 % in DJF. A curious result is a more pronounced anticorrelation with precipitation in Australia in JJAS and a positive correlation in central and northern Africa in DJF by 2100. These changes signify an enhanced predictability of precipitation based on the ENSO phase. According to half-year-lagged correlations, the precipitation over Australia, Indonesia and eastern Africa seems to be well predictable from the ENSO phase in both JJAS and DJF, if the ensemble view is applied [3].

We studied the Arctic Oscillation (AO) and its teleconnections, both in the MPI-GE and the CESM1-LE. We have shown in detail that the traditional, time-based computation of the AO index brings subjectivity to the investigation of the AO-related phenomena. We developed the SEOF analysis, based only on the instantaneous fields of the ensemble. We found that the AO's amplitude increases and the Pacific center strengthens considerably during climate change. Additionally, there exist such regions where the strength of the teleconnections of the AO shows remarkable variability [4,5].

We utilized five climate ensembles and 31 CMIP5 (Coupled Model Intercomparison Project Phase 5) models' simulations and showed that all models exhibit limitations in replicating the magnitude of the observed local atmosphere–sea ice coupling in the Arctics and its sensitivity to remote tropical SST variability, a teleconnection that we explained by a Rossby wave train mechanism. These

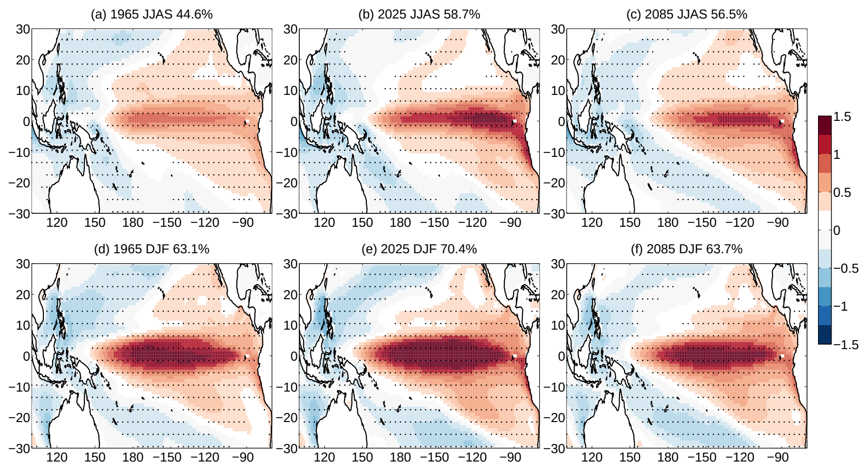

Figure 1: SEOF illustration in the CESM1-LE: ensemble-based SST regression maps [°C] for years given in the panels' title for JJAS (a-c) and DJF (d-f). The coloring in the regression maps corresponds to the typical SST anomaly values [°C] associated with the first SEOF. The variance explained by the first SEOF mode is also displayed in the title of the panels. Dots represent geographical locations where the regression coefficient is significant at the 95% level. For better visibility, only every fourth grid point is dotted. Figure is from [3].

biases call for caution in the interpretation of existing models' simulations regarding sea ice variability in the Arctic [6].

We studied the intensity of the spreading of atmospheric pollutants between 1979 and 2015 in reanalysis meteorological data by using the RePLaT particle-tracking dispersion model developed by us earlier, in the framework of OTKA project 100296. The intensity of the spreading was characterized by the stretching rate. The shape of its zonal distribution has been found to be similar for each of the studied years, however, we found a clear increasing trend in time, possibly due to the changing climate, implying that the prediction of the pollutant cloud becomes more difficult [7].

We studied atmospheric spreading in two ensembles of climate simulations as well: one was produced by us with the Planet Simulator (PlaSim) climate model, and the other was the CESM1-LE; both address century-scale climate change. We showed that single-realization estimates of trends in the spreading intensity can be misleading. However, the change in the intensity can be determined clearly based on the whole ensemble. The length of 10-day-old pollutant clouds decreased in general by 40 % during 100-year-long time periods in both models, which results in larger pollutant concentrations for several geographical regions. We revealed that the correlation of the stretching rate is the strongest with the absolute value of the relative vorticity among several meteorological variables. This relationship may help estimate the changes in the spreading intensity for arbitrary ensemble members utilizing only operationally computed meteorological variables, without carrying out computationally demanding dispersion simulations [8].

We investigated the chaotic properties of the lifetime and deposition of atmospheric aerosol particles emanating, e.g., from volcano eruptions. We have shown that the number of particles not yet deposited from the atmosphere decays exponentially after a while, which is characteristic to transient chaos. We found that the geographical distribution of the individual lifetimes shows a filamentary, fractal distribution. These maps can be considered as atlases for the potential fate of volcanic ash clouds. Particles emanating around the Equator were found to remain in the atmosphere for the longest time, even for years. The escape rate did not show any considerable dependence on the particles' initial altitude indicating that there exists a unique chaotic saddle in the atmosphere. We reconstructed the time evolution of this saddle and that of its stable and unstable manifolds [9].

Schumann resonances (SRs) are global electromagnetic resonances of the Earth-ionosphere cavity maintained by the vertical component of lightning. We analyzed 19 days of global lightning activity in January 2019 based on SR intensity records. The results are compared with independent lightning observations provided by ground-based and satellite-based lightning detection. We found that daily average SR intensity records from different stations exhibit strong similarity in the investigated time interval. The inferred intensity of global lightning activity varies by a factor of 2–3 on the time scale of 3–5 days which we attributed to cold air outbreaks from polar regions [10].

A set of PlaSim ensemble simulations with different forcing histories in total solar irradiance (TSI) indicates that even the steepest observation-consistent increasing trend in TSI without any change in CO_2 concentration is not sufficient to produce outcomes compatible with the observed global mean surface temperature. As a novelty, this conclusion is drawn such that spurious trends in the distribution of the modelled global mean surface temperature, possibly arising from an incomplete convergence to the relevant attractor, are excluded. This verifies that the ongoing global warming has a dominantly antropogenic origin with all of its implications for relevant policies [11].

Concerning the effect of major variations in the forcing, we investigated the so-called snowball Earth transition in the framework of an ensemble of PlaSim simulations. For certain values of the solar constant (TSI), the climate dynamics allows the existence of two different stable attractors: the snowball Earth, covered by ice and snow, and a warm attractor corresponding to today's climate. We considered a case when the climate system starts from its warm attractor, and the solar constant is decreased continuously but abruptly over one year, to a state where only the snowball Earth remains stable. This induces a tipping (i.e., an abrupt transition) from the warm climate (tipping in low-dimensional systems is discussed in Section iii). However, if the solar constant is increased back with a certain timing, the system returns to the warm attractor with a certain probability. In such a case, the snapshot attractor of the system splits between the warm attractor and the snowball Earth [12].

Teleconnections can only be investigated properly if the relevant probability distribution is unique. In the presence of slow system components this distribution may be conditional on the values of the slow variables, and we have pointed out that a time evolution in these values, if uniqueness is preserved, describes an unforced climate change in the faster system components. We have also found that uniqueness may be lost if the initialization of the ensemble numerically representing the probability distribution takes place during a regime transition in a slower system component. We propose an initialization scheme to investigate these issues. A confirmation of conditionality would call into question whether current practices for initialization are appropriate [13].

We completed a review-type article summarizing the advantage of the use of ensemble methods and their many application in climate research, in which this approach is called "the theory of parallel climate realizations" [14].

We have shown in the CESM1-LE that the growth rate of uncertainty (an analog of the Lyapunov exponent) can be determined right after initialization. Concerning a credible simulation, the observed signal should wander within the spread of an ensemble converged to the attractor all the time. We argue that the existence of "parallel climate realizations" is reflected by the probability distribution of the ensemble in a credible simulation. We formulated a novel, extended credibility condition, which requires the climate ensemble to be a converged one. This condition also holds for low-dimensional models with their own ensembles. Surprisingly, no low-order physical or engineering systems subjected to time-dependent forcings are known for which a comparison between simulation and experiment would be available. As illustrative examples, the CESM1-LE climate model and a chaotic pendulum were taken [15].

The scientific impact of our results is reflected in that Clara Deser (NCAR) invited us to publish an article [5] in the CLIVAR newsletter about the methodology applied in [4]. Since the CLIVAR publication, our ensemble-based methods have been used by other research groups, resulting in papers published by leading experts of the field: e.g., Maher et al., Large ensemble climate model simulations: introduction, overview, and future prospects for utilising multiple types of large ensemble, Earth System Dynamics 12, 401–418 (2021); O'Brien and Deser, Quantifying and Understanding forced changes to unforced modes of atmospheric circulation variability over the North Pacific in a coupled model large ensemble, J. Clim. 36, 19–37 (2022). Bin Guan (JPL, UCLA) also invited us to publish a chapter about the Northern Annular Mode in the book Atmospheric Oscillations, to be completed next year. As a spin off of our results to another area where nonergodicity is important and the ensemble view is essential in a system of high degrees of freedom, we conducted parallel research on spin glasses. Relevant techniques are summarized in a review article type book chapter [16] of a book with a Nobel Prize winner among its editors.

(ii) Is the ensemble approach a proper way to address (climate motivated) hydrodynamical experiments with inherently turbulent dynamics?

Certain general characteristics of the dynamics in turbulent flows driven by time-dependent thermal or mechanical forcing can be studied in laboratory experiments, which often prove to be surprisingly accurate models of environmental phenomena ranging from tornadoes to the general ocean circulation.

The differentially heated rotating annulus is a widely studied experimental model of the mid-latitude atmospheric and ocean circulation in which the fundamental underlying dynamics of baroclinic instability, Rossby waves, cyclogenesis, circumpolar jets, etc. can be reproduced to a conceptual level, obeying the principle of hydrodynamic similarity.

The set-up consists of a cylindrical tank mounted on a turntable and revolving around its axis of symmetry. The tank is divided into three sections by heat conductive coaxial cylindrical walls, which enables the experimenters to set a radial ("meridional") temperature contrast as a thermal boundary condition to drive the convective base flow. This configuration is a minimalistic representation of the mid-latitude atmospheric or ocean circulation.

The extensive testing of the heating and cooling thermostats revealed that – somewhat contrary to our expectations and our initial research plan – the reproducibility of the time- dependent thermal boundary conditions (forcing) in this system did not yet reach the required precision necessary for the originally proposed "slow-ramp" climate change ensemble experiments (the required technical changes are now underway). However, the apparatus has turned out to be an excellent test-bed for modeling abrupt "jump-wise" climatic events, particularly the opening of the Drake passage ca. 34 million years ago, which yielded one of the most pronounced global cooling events in Earth's climate history. We found that, seemingly contradicting paleoclimate records, the removal of a blocking meridional barrier resulted in higher values of mean water surface temperature than the original "closed" configuration. The mismatch pointed to the importance of the role ice albedo feedback plays in such an abrupt climate change, a component that was not captured in the laboratory model. This conclusion is supported by numerical runs performed in the PlaSim global climate model. These numerical results indicated that sea surface temperatures would change in the opposite direction with a more realistic ice-dynamics setting. The finding provides circumstantial evidence supporting a scenario in which Antarctica has already been covered with ice when the Drake Passage opened [17, 18].

We note that further results from our experimental projects using the rotating annulus setting – conducted in collaboration with different geophysical fluid dynamics laboratories – are discussed in Section iv as they are focusing on the extreme temperature statistics of the "weather in the tank".

In a different set of experiments related to environmental flows we studied vortices of arbitrary time dependence. According to the theoretical framework established by G. Haller and coworkers at ETH Zurich, three-dimensional time-

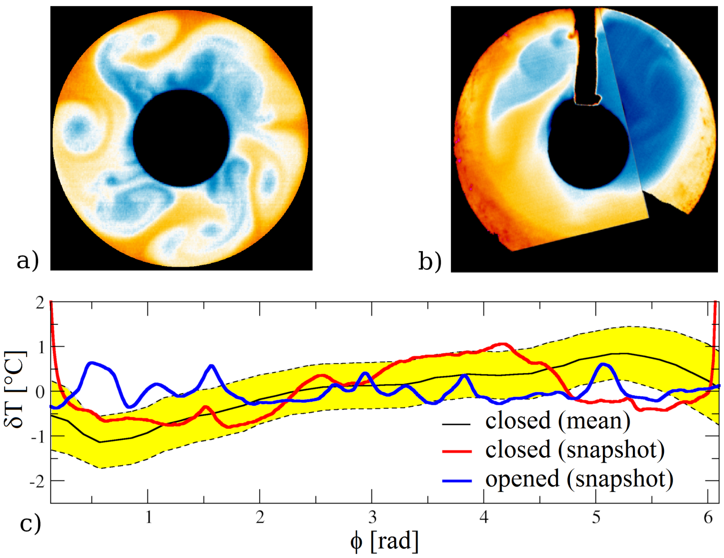

Figure 2: Exemplary infrared camera images of the surface temperature anomaly fields of the differentially heated rotating annulus in the “open” (a) and “closed” (b) configurations. The inner cylinder (black circle in the center) is cooled whereas the outer rim of the cylindrical tank is heated, thus providing buoyancy forcing for the circulation. (c) Mid-radius azimuthal temperature anomaly profiles extracted from the data of panels a) and b) (blue and red, respectively) and the time-averaged azimuthal profile of the “closed” configuration as measured with an infrared sensor. Source: [17].

dependent vortices, so-called elliptic "Lagrangian Coherent Structures", should be defined as rotating, material-holding tubular regions of the fluid. Our experiments supplied the first pieces of evidence supporting the theory, and they did so using a very elementary set-up. The measured data also provided information about quantities not predicted by the theory, e.g. the lifetime of dye spent within the vortex. We showed that the radius of the dyed cylinders, i.e., the horizontal extent of the vortex, hardly depends on the rotational frequency of the stirrer bar, but increases with the length of the bar. A generalization of this finding leads to the conclusion that the size of the water-holding region of the vortices in nature might be proportional to the size of the surface (or pressure) depression accompanying the vortex [19]. We also explored the demonstrative power and educational value of this magnetic stirrer-driven set-up (see section “Science education,...”) which appears to be a remarkably useful tool to make students familiar with the material holding character of vortices, which is a rather robust, generally observable property of vortices in nature, and as such, has been used as the basis of the aforementioned definition of a vortex.

We also extended our analysis to differentially rotating water-filled cylindrical settings, in which shear instabilities emerge and create so-called "polygonal vortices" at the water surface. Our results indicated that the propagation of these peculiar patterns can be interpreted accurately if we apply a properly rescaled linear water surface wave theory in this rather unique geometry [20].

Based on instrumental observations of vortices in the ocean recorded in the well-studied oceanic region along the shorelines of Oregon and California, we investigated mesoscale eddies, i.e., swirling flow patterns in the open ocean with diameters of around 100 km. They transport a huge amount of heat and material and are therefore key elements of the "weather" of the ocean. Using satellite-based ocean surface elevation data from large regions of the Pacific, we calculated the total energy of the near-surface flows and the percentage "stored" in the swirling motion. This percentage is found to be universal for various off-shore regions within the investigated domain along the West coast of the continental USA. This universality means that the combined global effect of *all* mesoscale eddies can be treated as a single strong "super-vortex". This finding is rather helpful to estimate the energy budget of ocean regions where only sparse field data is available [21].

We also concluded that the kinetic energy and vorticity of the geostrophic flow field in the area are mostly generated along the shorelines and advected to the open water regions, where the net wind stress work is almost negligible. Our results support that the geostrophic flow field is quasistationary on the timescale of a couple of days, thus total forcing is practically equal to total dissipation [22].

(iii) How can physical systems with arbitrary time-dependence be understood with the help of ensemble simulations?

Motivated by climate change, we explored how low-dimensional systems subjected to monotonous parameter drift should be properly studied, and how appropriate ensembles can be chosen. We showed that these systems essentially undergo their own climate change if the parameter drift is sufficiently strong.

A central aim of our research was to find methods for the identification of chaos in drifting systems where most of the traditional methods cannot be applied. The results of this effort were published in a sequence of papers.

In [23], we have extended the snapshot attractor view of dissipative systems to Hamiltonian systems subjected to different scenarios of parameter drift. The dynamics of such systems can best be understood by following ensembles corresponding to tori of the initial system. When such ensembles are followed, torus-like objects called snapshot tori are found to change with time, but ultimately they break up and spread over large regions of the phase space. Within the chaotic seas, we demonstrated the existence of a snapshot Samle horseshoe structure (in other words, a time-dependent chaotic saddle), the building block of chaotic dynamics [23].

In [24], the investigation was extended to discrete-time systems (mappings), with a discontinuity in their dynamics. Here too, the use of snapshot tori for the description of the system turns out to be appropriate. Tori eventually break up here as well, going through the same process as described above.

In dissipative systems without any driving all motion stops ultimately since the initial kinetic energy is dissipated away during time evolution. If chaos is present, it can only be of transient type, being supported by an infinity of unstable orbits. In the lack of these, chaos in undriven dissipative systems is of another type: it is termed doubly transient chaos as the strength of transient chaos is diminishing in time, and ceases asymptotically. We have shown that a clear view of such dynamics is provided by identifying ensembles on KAM tori or chaotic regions of the dissipation-free case, and following their time evolution in the dissipative dynamics [25]. Here the perpetual decrease of the mechanical energy can be considered to be a special parameter drift. This was also detailed in the review paper [26], where we defined the existence of a non-adiabatic parameter drift as a climate change in mechanical systems.

In [27], it was shown that perhaps the most general phase space-related characterization is provided by the stable and unstable foliations. They are shown to be easy to approximate numerically even in the presence of parameter

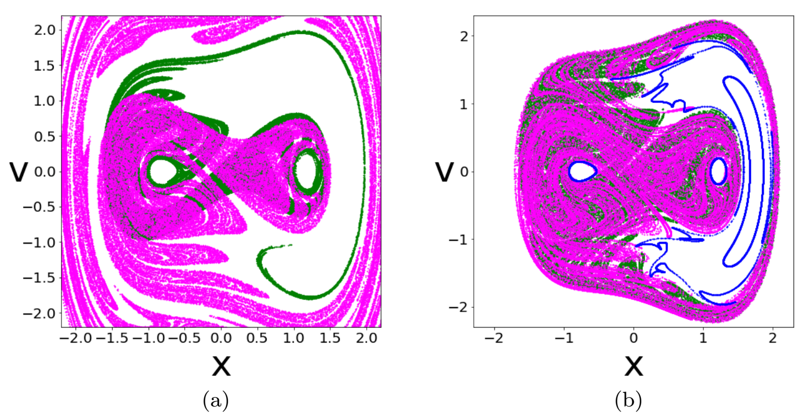

Figure 3: Time-dependent unstable (green) and stable (pink) foliations of the Duffing oscillator system subjected to parameter drift, overlaid on top of each other, making a time-dependent Smale horseshoe. (a) Dissipative case with weak driving. Here time-dependent regular attractors coexist with chaos, thus the snapshot attractor is not fully chaotic [28]. (b) Hamiltonian case. Here the foliations are not identical because of the lack of time-reversal symmetry, and do not cover each other fully either, because of the existence of the time-dependent non-hyperbolic regions [28]. Some snapshot tori, first introduced in [23], that had not been broken up so far in the scenario are also shown as blue curves.

drift, without relying on the existence of an analog of unstable periodic orbits. Chaos originates from a horseshoe-ike pattern of the snapshot foliations, the transverse intersections of which indicate the existence of a chaotic saddle changing in time. In dissipative cases, the unstable foliation is found to be part of the snapshot attractor. In Hamiltonian cases, stable and unstable foliations turn out to be non-equivalent due to the lack of time-reversal invariance. It is the unstable foliation that is found to correlate with the so-called snapshot chaotic sea.

The research during the last year concentrated on yet open problems [28]. We have shown that if regular time-dependent attractors coexist with the snapshot attractor, the chaotic set is not dense on the snapshot attractor. In this case, the snapshot attractor is only partially chaotic: it supports an example of transient chaos. The basins of the regular time-dependent attractors are fractal-like. At any instant, they accumulate on the stable foliation, and might exhibit the Wada property. In Hamiltonian cases, non-hyperbolic effects are identified, and it is shown that the snapshot chaotic sea does not need to be fully chaotic.

The quantity called ensemble-averaged pairwise distance, EAPD, introduced in [23], turns out to be an appropriate tool to provide a quantitative measure of time-dependent chaos. The EAPD provides the typical time-dependent growth rate of initially nearby trajectories averaged over the ensemble. Its slope at a time instant corresponds to an instantaneous Lyapunov exponent. The EAPD is evaluated in all the cases treated in [24–28] and provides a rich variety of shapes. In a Hamiltonian case, the EAPD evaluated for a torus hardly changes initially but crosses over into an exponential growth when the snapshot torus breaks up, signalling chaotic dynamics after that point. For doubly transient chaos, again with the ensemble of a torus, the growth stops at some time, and a decrease starts with a negative slope, indicating that chaos is no longer present.

As a more applied, climate-related system, we investigated a low-dimensional coupled atmosphere–phytoplankton model under climate change due to a varying strength of anthropogenic atmospheric forcing, including the following couplings: (a) the temperature modifies the total biomass production via the carrying capacity; (b) the extraction of carbon dioxide by phytoplankton slows down climate change; (c) the strength of turbulence in oceanic mixing layer correlates with phytoplankton productivity. Using an ensemble approach, we concentrate on the trends of the phytoplankton concentration and the temperature contrast between the pole and the Equator, and determine the low-dimensional snapshot attractor. The conclusion is that the phytoplankton concentration and its coupling to climate are able to enhance global warming [29].

Recently, we also applied the methods developed in chaos theory to galaxy dynamics. Here, we investigated the so-called generalized Myamoto-Nagai model, subjected to linear parameter drift of the total mass of the galaxy. We observed the break-up of snapshot tori, the formation of time-dependent non-hyperbolic regions, and the emergence of chaos. We applied the EAPD method here as well, measuring the instantaneous Lyapunov exponent of torus break-up. The results of this work are summarised in the preprint [30].

Going beyond the usual characterization, a more refined view is also offered based on identifying ensembles of trajectories that follow a certain type of *history*. The process can be considered to be a leaking in history space, a generalization of traditional leaking, a method that has become widespread in traditional chaos theory, to leaks depending on time [31]. Prescribing a history is necessarily a restriction, and trajectories fulfilling this constraint are of finite lifetime, representing transient chaos, whose different forms of appearance are overviewed in [32].

Tipping phenomena, i.e., dramatic changes in the long-term performance of deterministic systems subjected to parameter drift, are of current interest but have not yet been explored in cases with chaotic internal dynamics. We show that a number of novel types of tippings can be observed: tippings from and into several coexisting attractors, fractality-induced tipping, as well as tipping into chaos. Rate-induced tippings do not appear abruptly, rather, they show up gradually when the rate of the parameter drift is increased. Since systems of arbitrary time dependence call for ensemble methods, we propose the use of tipping probabilities as a measure of tipping, and determine these quantities for all tipping forms in [33].

We also studied a bifurcation cascade whose proper unfolding requires tuning more than one parameter simultaneously. Specifically, we investigate metric properties of extended self-similar triangular areas observed recently in the control parameter space of flows (lasers and electronic circuits) and maps. Such areas are delimited by shrimplike stability islands, which seem to arise in unbounded quantities and to accumulate in narrow intervals of control parameters. The asymptotic properties of triangle vertices and their centroids are also investigated [34].

The scientific impact of our results is reflected in that paper [23] appeared as an Editor's Pick of the journal Chaos, and paper [26] was published in Nonlinear Dynamics as a Feature Article, a collection to which papers are selected by an editorial invite. Motivated by the climate-related methods summarized in [14], a low-dimensional model was created for epidemic dynamics under changing vaccination coverage as a parameter drift: T. Kovács: How can contemporary climate research help understand epidemic dynamics? Ensemble approach and snapshot attractors, J. R. Soc. Interface 17, 20200648 (2020). The approach of [33] to tipping phenomena was generalized to time-delayed systems by J. Cantisán et al, Transient chaos in time-delayed systems subjected to parameter drift, J. Phys. Complex. 2, 025001 (2021).

(iv) The extension of extreme value statistics and time series analysis to systems that show both strong correlations and time-dependent trends

The investigation of extreme behavior is a very wide field of science. Our research covers certain aspects of this, ranging from laboratory measurements, via data extracted from observations and climate simulations, even to low order models.

In collaboration with the geophysical fluid dynamics laboratory of the Brandenburg University of Technology (Cottbus, Germany) and the Geophysical Fluid Dynamics Institute of the Florida State University (Tallahassee, USA) we have performed two series of long experimental runs in two differentially heated rotating annulus set-ups of markedly different geometrical dimensions. We have evaluated time series of extreme temperature fluctuations from these long-duration laboratory-scale models of the mid-latitude climate exhibiting inherently turbulent circulation. The statistics obtained from the two different configurations revealed certain universal scaling properties which characterize the frequencies of large thermal fluctuations in the systems and the persistence of the model "weather", and the distributions of extreme temperature events have been shown to follow the Generalized Pareto Distribution (GPD) class, widely used to characterize extreme value statistics. The analysis of the timescale associated with the largest persistence in the temperature records from these experiments – as well as the observation of the shifting cut-off frequencies in their red noise-like spectra – revealed that with an increasing meridional temperature contrast a widening spectral domain is characterized by red-noise-like behavior (instead of being uncorrelated white noise). In agreement with the qualitative predictions of the Correlated Additive and Multiplicative noise-driven time series model and also with our observations, this spectral change is accompanied with the widening of the histograms of the point-wise temperature fluctuation time series [35].

In another set of experiments, also conducted in collaboration with the Brandenburg University of Technology, we have investigated the effect of polar warming on the mid-latitude jet stream. Our results showed that a progressive decrease in the meridional temperature difference slows down the eastward propagation of the jet stream and complexifies its structure. The temperature variability decreases in relation to the laboratory-analogue of the "Arctic Warming" only at locations representing the Earth's polar and mid-latitudes, which are influenced by the jet stream, whilst such a trend is reversed in the subtropical region south of the simulated jet. The reduced variability results in narrower temperature distributions and hence milder extreme events. We found qualitatively similar trends of temperature variability and extreme events in the experimental data and the National Centers for Environmental Prediction (NCEP) reanalysis data [36].

Wind speed and solar irradiation data of high spatial and temporal resolution are analyzed for an extended area of north-western Africa with the aim of judging the potential of combined wind-solar electricity production. To this end the observation-based data of the ERA5 data bank are exploited. This data bank provides the horizontal wind speed at a height of 100 m (modern wind turbines have a hub height between 80 and 120 m), a quantity strongly fluctuating in time. We have demonstrated that the desert area is an optimal location for wind and solar electricity production because wind speed differences between the standard 10 m altitude and 100 m level are on average considerably larger over the desert area than over the sea. Moreover, we find anticorrelations between local wind speeds at 100 m and surface solar radiations over the Sahara, and point out that this is an exploitable source of combined solar-wind electricity production. A theoretically optimal combination of the two resources is found in a simple model. The result is that wind-solar resource combinations between 60-40 % and 70-30 % (depending on the geographic location) provide an optimal output [37].

In a biology-related context, in order to identify the most relevant fluctuating climatic parameters that regulate flowering time of bulbous perennials, flowering dates of 329 taxa over 33 yr are correlated with monthly and daily mean values of 16 environmental parameters (such as insolation, precipitation, temperature, soil water content, etc.) spanning at least 1 year back from flowering. A machine learning algorithm is deployed to identify the best explanatory parameters. Surprisingly, the best proxy of flowering date fluctuations is the daily snow depth anomaly, which cannot be a signal itself, however, it should be related to some integrated temperature signal. Moreover, daily snow depth anomaly as a proxy performs much better than mean soil temperature preceding the flowering, the best monthly explanatory parameter. Our findings support the existence of complicated temperature sensing mechanisms operating on different timescales, which is a prerequisite to precisely observe the length and severity of the winter season and translate, for example, "lack of snow" information to meaningful internal signals related to phenophases [38].

A particular aspect of climate change, the water cycle and its change over the last decades, is investigated in [39] with a focus on the Carpathian (Pannonian) Basin. Observations indicate an accelerating and intensifying water cycle in this region. In three hydrometric stations along the river Tisza the time series of the water level are also analysed over the last twenty years. The data are found to be correlated, but a clear annual periodicity is not easy to resolve. Extreme behavior was identified with maxima and minima of the water level in a given year. The time of the annual peak water levels (not necessarily floods) are found to be shifted to later days of the year, while annual minimum water

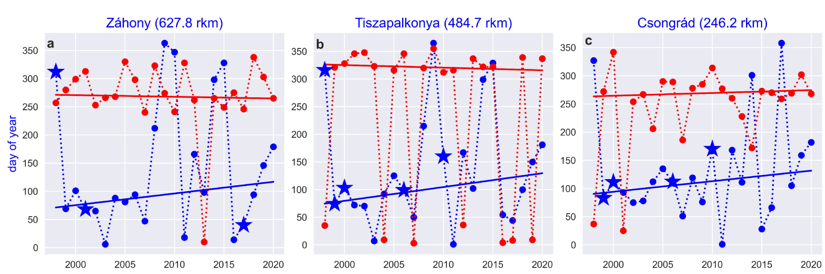

Figure 4: Day of the year when the water level is extremal: it takes on its annual maximum (blue) and minimum (red) at three hydrometric stations (see title lines) along the river Tisza. Linear fits (straight lines) are also given. Stars indicate real flood events. Source: [39].

levels exhibit much weaker tendencies.

To explore climate-change-induced irregularities in oceanic advection, we have performed numerical experiments in a region of the tropical Pacific, where 6600 tracer parcels are advected from a regular initial configuration (along a meridional line) over periods of 1 year for 25 years altogether. We have exploited the AVISO surface flow field data, and solved the kinematic equation for passive tracers. We have demonstrated that the strength of advection defined by the mean of the monthly westward displacements of the tracer clouds exhibits surprisingly large inter- and intra-annual variabilities. Furthermore, an analysis of cross-correlations between advection strength and the Oceanic Niño Index (ONI) and the Southern Oscillation Index (SOI) revealed a significant anticorrelation between advection intensity and ONI, and a weaker positive correlation with SOI, both with a time lag of about 3 months. The model parameters are fitted, and by numerical simulations of the fractional Brownian motion model we show that this correlated stochastic model is able to reproduce the observed statistical properties of the tracer trajectories very well [40].

In ensemble simulations of the climate, extreme behavior can be explored via a novel approach [41], based on a zooming in into the ensemble. To this end, additional, small sub-ensembles are used, and plume diagrams initiated on the same day of a year are generated from these sub-ensembles. Trajectories within the plume diagram strongly deviate on the time scale of a few weeks. By defining the extreme deviation as the difference between the maximum and minimum values of a quantity, a growth rate for the extreme deviation can be extracted. An average of these taken over the original ensemble characterizes the typical, exponential growth rate of extremes. The reciprocal of this can be considered to be the characteristic time of the emergence of extremes, and is on the order of a few days. Measuring these times in the climate model PlaSim in several years along the last century, results for the global mean surface temperature turned out to be roughly constant, while for pressure a decaying trend was found in the emergence time of extremes in the last decades.

We have also developed a new method for the decomposition of noisy, nonstationary, complex signals. The methodology has grown out from the popular "Empirical Mode Decomposition" procedure, which is a top-to-bottom algorithm. In contrast, our decomposition runs from bottom to top (slowest "essential mode" first). The algorithm is based on smoothness-controlled cubic spline fits: a systematic scan is performed by cubic spline fits with an input parameter controlling the smoothness. Our main finding is that the growth rate of the so-called coefficient of determination is not monotonic: when an "Essential Slow Mode" is approached, the growth rate exhibits a local minimum. We demonstrate that this behavior provides an optimal tool to identify strongly quasi-periodic slow modes in non-stationary signals. As a practical climate-related application, we identified essential slow modes in daily ice extent anomalies both at the Arctic and Antarctic. Our analysis demonstrates the distinct freezing-melting dynamics on the two poles, where apparently different factors are determining the time evolution of ice sheets [42].

As another example of systems producing strongly correlated (periodic) and chaotic, i.e., noisy, signals, we have performed a detailed fine-scale study of the dynamical response over extended parameter ranges of a computationally inexpensive model, the two-dimensional Rulkov map, which reproduces well the spiking and spiking-bursting activity of real biological neurons. We have provided evidence for the existence of nested arithmetic progressions among periodic pulsing and bursting phases of the Rulkov neuron. We have found that specific remarkably complex nested sequences of periodic neural oscillations can be expressed as simple linear combinations of pairs of certain basal periodicities [43].

Science education, outreach and impact

To ensure a broader impact of our research, we kept focusing also on education/outreach activities. We tried to convert our recent scientific achievements into popular science or high school teaching, following by this a direction called educational reconstruction in education science.

Thus, as a conversion of our results on pollutant spreading [7–9], we developed an application called RePLaT-Chaos-edu. By means of this freely available program, students can investigate the characteristics of air pollutant dispersion. It is also a suitable tool for studying the chaotic features of advection [44]. The software was tested at the Berzsenyi Dániel Grammar School and the Szent István Grammar School (Budapest, Hungary) in the framework of Physics classes and during a project week, respectively [45]. Based on the results of [9], an interview was published on the web page of the American Institute of Physics (AIP) Publishing, mentioning also this computer game. The interview was taken over by a number of international forums.

Similarly, as a continuation of [19], we carried out a simplified set of experiments with vortices of arbitrary time-dependence. Our aim is to show that it is very easy to demonstrate the water/material holding property of vortices

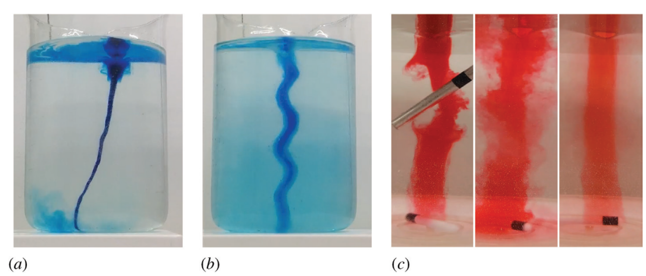

Figure 5: A physics class demonstration of the extreme stability of a three-dimensional vortex as a "Lagrangian Coherent Structure", and its material holding property. A vortex captures dye even if it is tilted (a), if it becomes a snake vortex after "kicking" the container, or if it is cut through by a rod (c). Source: [46].

by means of magnetic stirrers, and that such experiments can be carried out in schools to let students be aware of this property observable in vortices occurring in nature (e.g., in tornadoes) [46]. Another vortex-related issue, convection over zebra stripes was discussed in a popular science magazine article [47].

Our experience in environmental issues and climate change motivated us to write for a general audience about effects resulting from the rotation of the Earth [48, 49], environmental awareness [50], and global questions related to climate change [51].

Different facets of chaos observed during this project led us to call the attention of secondary school students to an everyday example, the bouncing of a ball down the stairs [52]. A short teaching material emphasizes the role of plume diagrams, and also illustrates the distinction between chaos in low and high dimensions [53]. Paper [54] points out that the "ensemble view" can be useful even in a proper interpretation of quantum uncertainty.

We organized lab visits, prepared dissemination talks in a student-friendly language, and presented them upon request at public educational institutions. Several results obtained in the framework of this project acquired enhanced attention in Hungarian printed and online public media.

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