The 6th Bremen Winter School and Symposium

Dynamical Systems and Turbulence

March 12-16 2018

Fachbereich Mathematik & Informatik
Universität Bremen

Book of Abstracts and Programs
The 6th Bremen Winter School and Symposium

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Energy Transfer in Atmosphere and Ocean
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ADMINISTRATIVE CONTACT
Ebba Feldmann
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Course: **Mon**, 09:00-10:30, 10:50-12:20; **Tue**, 10:50-12:20

The problem of turbulence: bounding solutions to equations of fluid mechanics & other dynamical systems

Sergei Chernyshenko*,†, Giovanni Fantuzzi†,†

Advances in computing technology have enabled the calculation of complex and chaotic solutions to nonlinear dynamical systems, including in some cases turbulent solutions to the fundamental equations of fluid mechanics. However, numerical simulations have two inherent drawbacks. The first is that one is often interested only in a few quantities, such as the lift and drag of an aircraft, but computing them typically requires very high-fidelity simulations, whose computational cost can be prohibitive. The famous problem of turbulence consists in discovering rigorous and computationally efficient methods to calculate only the quantities of interest, without having to compute also the fine details of the flow. The second drawback is that, even when a mathematical model is known to precisely represent a physical system, the approximation error of numerical solutions cannot be calculated exactly. In safety- or performance-critical applications, overcoming the uncertainty in numerical errors necessitates calculations with higher precision than essential, or even possible.

In the last few years a rigorous general approach addressing these drawbacks has been proposed. If X is the quantity of interest, the approach gives lower and upper bounds (A and B, respectively) such that X is mathematically guaranteed to lie between A and B. This bounding framework combines a generalisation of the century-long idea of a Lyapunov function with advances in computational semi-algebraic geometry made at the start of the millennium, and it is related both to the well-known nonlinear energy stability theory and

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to the "background method" for bounding time averages. The crucial observation is that the bounds A and B can be computed numerically without simulating the underlying system, thus promising a reduction in computational complexity compared to current practice. At the expense of additional computational cost, bounds can also be tightened systematically as much as needed to guarantee that any safety or performance specifications are met.

In these lectures and associated exercise sessions we will introduce the theory behind this new approach, showcase specific examples, and provide a hands-on experience of computing bounds for a few simple nonlinear systems.
Towards the computation of time-periodic inertial range dynamics

Lennaert van Veen*, 1, Genta Kawahara2, Alberto Vela Martin3, Atsushi Yasuda4

One of the great open questions in turbulence research concerns the way energy is transferred from large to small spatial scales. While the statistics of the transfer process are well-studied, its dynamics remain unclear. The spatio-temporal complexity of developed turbulence and its extremely sensitive dependence on initial conditions are largely to blame for this lack of understanding. One possible remedy is to compute simple invariant solutions that co-exist with turbulence and share its essential dynamics. Such invariant solutions can be thought of as building blocks, or models, of turbulence. Unfortunately, their computation is quite challenging. Extrapolating from known results for fluid motion on small domains near the onset of turbulence, we can easily estimate that finding a good model for developed turbulence is beyond our current capabilities. In this presentation, I will review some recent attempts to use Large Eddy Simulation of fluids as a short cut to studying turbulent dynamics. In LES, the smallest scale motion is modelled, rather than resolved, and thus the number of degrees of freedom is drastically reduced. We will look at recent attempts to use this technique in wall-bounded and homogeneous shear flow and focus in particular on our recent work on flow on a periodic domain, i.e. box turbulence. Depending on the progress of ongoing computations, I will place more emphasis on promising preliminary results or on the difficulties presented by LES as a computational dynamical system.

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1University of Ontario, Canada
2University of Osaka, Japan
3Polytechnic University of Madrid, Spain
4Imperial College London, UK
Talk: Mon, 14:25-15:25

Towards the computation of time-periodic inertial range dynamics

Björn Hof*, 1

In channels and pipes turbulence first appears in the form of localise patches surrounded by laminar flow. I will here discuss how the dynamical systems approach can help to explain the occurrence of such localised puffs (in pipes) and of turbulent stripes (in channels). Starting from the marginal boundary between laminar and turbulent flow we identify travelling wave and periodic orbit solutions that then undergo a sequence of instabilities and the dynamics becomes chaotic. With a further increase in Re the dimension of the chaotic set rapidly increases. While with increasing Reynolds number also lifetimes decrease under certain conditions the low Reynolds number chaos emerging from periodic orbits can be smoothly connected to turbulent stripes at higher Re.

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1Institute of Science and Technology, Vienna, Austria
Turbulence closure modelling in the coastal ocean: the essential effect of stable stratification on vertical mixing

Hans Burchard*

Small-scale turbulent mixing in the ocean is highly variable, with eddy viscosities and diffusivities ranging over several orders of magnitudes. While turbulence in the nearly unstratified surface and bottom boundary layers is generally high and only bounded geometrically by the thickness of the boundary layers, turbulence in the stratified interior is strongly suppressed. Specifically in the coastal ocean, temporal variability is high and boundary layers may occupy a substantial part of the water column. In this presentation, turbulence closure models are introduced which account for this spatial and temporal variability. Two-equation turbulence closure models are argued to be an optimal compromise between efficiency and accuracy for the purpose of calculating vertical fluxes of momentum, heat and tracers in coastal ocean modelling. They provide enough degrees of freedom to be calibrated to the most prominent properties of coastal ocean mixing, but are still numerically robust and computationally efficient. One essential ingredient for a working turbulence closure in the ocean is the proper calibration of the suppression of vertical mixing by stratification. Major implementational and numerical aspects are presented. Some focus will be on the inherent problem of numerically-induced mixing which together with the physically-induced mixing gives the effective mixing in ocean models. Vertically adaptive coordinates are presented as one possibility to reduce numerical mixing. Some examples for thermocline mixing in the Northern North Sea, physically and numerically induced mixing in the Western Baltic Sea as well as basinwide mixing in the Central Baltic Sea are presented. All three examples highlight the importance of using well-calibrated turbulence closure models together with vertically adaptive coordinates.

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1Leibniz Institute for Baltic Sea Research Warnemünde, Rostock, Germany
Talk: **Tue, 14:25-15:25**

**Paths in a turbulent ocean**

Ana Maria Mancho*,1

Finding order in the apparent chaos that seems to describe how different tracers are transported in the ocean is a challenge. Describing transport is however of vital importance to support decision making in emergencies, as for instance a spill event, as it allows predicting and assessing its impact. In this talk I will provide an overview of recently developed tools, the so called Lagrangian Descriptors [1–3], which display beautiful geometries highlighting the always changing dynamical skeleton of the ocean. I will illustrate applications of these objects to the operational management of coastal emergencies such as the sinking and subsequent fuel spill by the Oleg Naydenov fishing ship in the Gran Canaria coast, Spain in April 2015 [4].

References


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1ICMAT, Madrid, Spain*
Public Lecture: **Tue, 18:00-19:00**

**How pipe flow becomes turbulent - a matter of life and death**

Björn Hof*,1

Fluid flows can either be smooth and laminar or disordered and turbulent. Although in pipes the laminar state is in principle stable, in practice almost all flows are turbulent causing a drastic increase in friction losses. Although this problem has been intensely studied for over a century, the nature of the transition could not be explained.

As will be shown this riddle can be resolved by considering the onset of turbulence as a spreading phenomenon where laminar domains compete with turbulent regions. In analogy to a basic statistical physics model the onset of turbulence can then be understood as a continuous phase transition and an exact critical point can be defined.

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1Institute of Science and Technology, Vienna, Austria
Course: **Wed**, 09:00-10:30, 10:50-12:20; **Thu**, 10:50-12:20

Spatiotemporal chaos

Paul Manneville*,1

We will scrutinize the emergence and some properties of spatiotemporal chaos, i.e. mild turbulence, in systems with dimensions large when compared to intrinsic scales generated by instabilities. The key characteristic is the slow dynamics in time and space that results from the proximity of a bifurcation and from the continuous symmetries typical of the unbounded-domain limit. A brief review of relevant elements of stability theory and bifurcation analysis will first be given. A key feature is the continuous or discontinuous nature of the primary bifurcation away from the system’s base state of interest. Considered first, the globally supercritical transition scenario takes place when the primary instability is continuous. This case is amenable to analysis via multiple-scale expansions that introduce envelopes and phases as natural tools apt to account for pattern formation and phase turbulence. The subcritical case implies the coexistence of concurrent locally stable states in both phase space and physical space. In extended systems, this leads to a spin-like reduction to be studied within the framework of statistical physics, hence an analysis of, e.g., spatiotemporal intermittency in terms of phase transitions and critical phenomena. To conclude, some general properties of far-from-equilibrium systems will be discussed.

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1LadHyX, École Polytechnique, France
Talk: Wed, 13:45-14:15

Thermal boundary layers in turbulent Rayleigh–Bénard convection

Olga Shishkina*,1, Emily S. C. Ching2

We consider a thermal boundary layer (BL) equation in turbulent Rayleigh–Bénard convection, which takes into account fluctuations in terms of an eddy thermal diffusivity [1–3] and make use of the idea of Prandtl's mixing length model and relate the eddy thermal diffusivity to the stream function. With this proposed relation, we can solve the thermal BL equation and obtain a closed-form expression for the dimensionless mean temperature profile in terms of two independent parameters. With a proper choice of the parameters, our predictions of the temperature profiles are in excellent agreement with the results of our direct numerical simulations of turbulent RBC for a wide range of Prandtl numbers (Pr), from Pr=0.01 to Pr=2547.9. The work is conducted in collaboration with Emily S. C. Ching, The Chinese University of Hong Kong.

References


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2The Chinese University of Hong Kong, Hong Kong, China

DYNAMICAL SYSTEMS & TURBULENCE 2018
Simulation of extreme heat waves in a climate model using a rare event algorithm

Francesco Ragone∗,1

Studying extreme events with complex climate models is computationally very challenging. To perform simulations that are long enough to properly compute the statistics of very rare events is often impossible. Rare event algorithms are methods developed for applications in physics, chemistry and biology, that are used to drive numerical simulations to oversample rare events of interest. In this talk I will present how we have applied such an algorithm to study European heat waves in a general circulation model. The method allows to compute the statistics of extreme events with return times of more than hundreds of thousands of years with simulations with a computational cost several orders of magnitude smaller. The improved statistics allows to show how European extreme heat waves in the model are related to a global teleconnection pattern involving North America and Asia. These tools, so far underexploited in climate modelling, could open a wide range of new possible studies to characterise on a robust quantitative basis the statistics and the dynamics of several classes of extreme events.

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Turbulent liquid metal flows in the presence of magnetic fields – numerical studies in wall-bounded geometries

Thomas Boeck*,1, Dmitry Krasnov1, Oleg Zikanov2, Vinodh Bandaru1, Jörg Schumacher1

Static magnetic fields interact with flowing conducting liquids due to electromagnetic induction. The induced eddy currents in such magnetohydrodynamic flows cause Lorentz forces that modify the flow. The effect of the flow on the external magnetic field is usually weak since the magnetic diffusivity of liquid metals is large. Homogeneous magnetic fields tend to eliminate velocity gradients along the field, which induces flow anisotropy. Eddy current distributions are also affected by the presence of walls, and give rise to specific types of magnetohydrodynamic boundary layers. The properties of turbulent flows and the transition to turbulence are therefore considerably different from hydrodynamic flows.

Duct flows in a magnetic field are not only important for technological applications, e.g. in metallurgy, but are also central to fundamental research. In recent years, numerical simulations have contributed significantly to the understanding of such magnetohydrodynamic flows. The talk will focus on flows in homogeneous magnetic fields. Transition to turbulence in duct flows with different wall conductivities will be analyzed, which depends either on linear or nonlinear instabilities of the laminar flows. The modification of the turbulent boundary layers due to magnetic damping will be discussed as well as high-speed flows in large ducts where the magnetic field is significantly modified by induction.

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1Technische Universität Ilmenau, Germany
2University of Michigan, Dearborn, USA
Talk: **Wed, 16:00-16:30**

**Chaotic advection in the Alboran Sea: Lagrangian analysis of the Western Alboran Gyre**

Genevieve Brett*,1

The Alboran Sea, just east of the Strait of Gibraltar, contains a large anticyclonic gyre, the Western Alboran Gyre. This gyre is bounded to the north by the Atlantic Jet, which carries Atlantic Water into the Mediterranean. This work uses output from an MIT general circulation model run to study the exchange of water between the gyre and the jet. The core of the gyre, where stirring is slow, is identified. Advective transport in the outer, chaotic region is described using a Lagrangian dynamical systems analysis, and is compared to Eulerian transport estimates. I show that horizontal advection of warmer fresher water into the gyre is the primary driver of changes in the gyre properties. Vertical diffusion between the surface and deep waters and surface forcing are of secondary importance.

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1Woods Hole Oceanographic Institution, USA
Talk: **Wed**, 16:40-17:10

**Turbulence and pattern formation in a minimal model for active fluids**

Michael Wilczek*, 1

Continuum theories of active fluids display a fascinating range of dynamical states, including stationary patterns and turbulent phases. While the former can be tackled with classical pattern formation theory, the spatio-temporal disorder of active turbulence calls for a statistical description. In this presentation, new results on turbulence and pattern formation in a minimal continuum model for active fluids, which has been recently proposed by Wensink et al. [1], will be discussed. Adopting techniques from turbulence theory, we establish a quantitative description of correlation functions and spectra for active turbulence. We furthermore report on a novel type of turbulence-driven pattern formation far beyond linear onset: the emergence of a dynamic vortex lattice state after an extended turbulent transient, which can only be explained taking into account turbulent energy transfer across scales.

**References**


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1Universität Göttingen, Germany
Recent advances in the subcritical transition to turbulence

Dwight Barkley*; 1

Recent years have witnessed a profound change in our understanding of the route to turbulence in wall-bounded shear flows such as pipes, ducts, and channels. These lectures will review our current knowledge of the dynamics of transitional turbulence on a wide range of scales. Considerable focus will be given to quantifying the complex spatiotemporal intermittency observed in experiments and numerical simulations. A theoretical underpinning of the route to turbulence in subcritical shear flows will be presented. Finally, lectures will include a discussion of outstanding open questions.

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Production of dissipative vortices by no-slip walls in incompressible flows in the vanishing viscosity limit

Kai Schneider*, ¹, Natacha Nguyen van yen², Marie Farge³

We revisit the problem posed by Euler in 1748 that lead d’Alembert to formulate his paradox and address the following question: does energy dissipate when boundary layers detach from solid body in the vanishing viscosity limit, or equivalently in the limit of very large Reynolds number Re ? To trigger detachment we consider a vortex-dipole impinging onto a wall. We compare numerical solutions of two-dimensional Euler, Prandtl, and Navier-Stokes equations [1]. We observe the formation of two opposite-sign boundary layers whose thickness scales like $Re^{-1/2}$, as predicted by Prandtl’s theory in 1904. After a certain time when the boundary layers detach from the wall Prandtl’s solution becomes singular, while the Navier-Stokes solution collapses down to a much finer thickness for the boundary layers in both directions (parallel but also perpendicular to the wall), that scales as $Re^{-1}$ in accordance with Kato’s 1984 theorem [2]. The boundary layers then roll up and form vortices that dissipate a finite amount of energy, even in the vanishing viscosity limit [1, 3]. These numerical results suggest that a new Reynolds independent description of the flow beyond the breakdown of Prandtl’s solution might be possible. This lead to the following questions: does the solution converge to a weak dissipative solution of the Euler equation, analog to the dissipative shocks one get with the inviscid Burgers equation, and how would it be possible to approximate it numerically [4, 5]?

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On the relevance of small-scale turbulence in planetary boundary layers

Juan Pedro Mellado* 1

Planetary boundary layers are important in climatology – modulating the fluxes between atmosphere, land and ocean, and in meteorology – influencing weather conditions, but key properties remain poorly understood, largely because the boundary layer is turbulent and understanding and characterizing the multi-scale nature of turbulence remains challenging. This multi-scale nature becomes particularly relevant near the surface and in the entrainment zone, where interactions on scales of meters between turbulence and density stratification, radiative transfer and cloud physics can affect the evolution of the whole boundary layer. During the last decade, direct numerical simulations have provided new insight into these interactions. I will use various examples to illustrate some of these recent advances, and to indicate potential developments during the coming years.

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4 Poster abstracts

Hyperbolic Covariant Coherent Structures in two dimensional flows

Giovanni Conti*,1, Gualtiero Badin†,1

A new method to describe hyperbolic patterns in two dimensional flows is proposed. The method is based on the Covariant Lyapunov Vectors (CLVs), which have the properties to be covariant with the dynamics, and thus being mapped by the tangent linear operator into another CLVs basis, they are norm independent, invariant under time reversal and can be not orthonormal. CLVs can thus give a more detailed information on the expansion and contraction directions of the flow than the Lyapunov Vector bases, that are instead always orthonormal. We suggest a definition of Hyperbolic Covariant Coherent Structures (HCCSs), that can be defined on the scalar field representing the angle between the CLVs. HCCSs can be defined for every time instant and could be useful to understand the long term behaviour of particle tracers. We consider three examples: a simple autonomous Hamiltonian system, as well as the non-autonomous “double gyre” and Bickley jet, to see how well the angle is able to describe particular patterns and barriers. We compare the results from the HCCSs with other coherent patterns defined on finite time by the Finite Time Lyapunov Exponents (FTLEs), to see how the behaviour of these structures change asymptotically.

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DYNAMICAL SYSTEMS & TURBULENCE 2018
A set-oriented method for the reconstruction of attractors using data

Raphael Gerlach∗,1, Michael Dellnitz1, Adrian Ziessler1

To understand the dynamics of turbulent flows we are reconstructing attractors from time series obtained from numerical simulations or experiments. To this end, embedding techniques [1, 2] allow us to use observations of the underlying system to get an one-to-one image of the attractor in an appropriate finite dimensional space. We approximate this set by box coverings utilizing the observed data [3, 4]. To obtain a good approximation, that is an appropriate covering, we study connected components. Finally, we compute the box-count dimension of this covering to determine the complexity of the flow.

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Entropy production in turbulence parameterisations

Denny Gohlke*,1, Richard Blender1

The physically consistent representation of turbulence subgrid-scale processes in forced dissipative systems like atmosphere and ocean requires the handling of statistical nonequilibrium fluctuations. The statistics of these fluctuations – as a fingerprint of the chaotic dynamics – provide useful insights into the dynamical response behaviour of a system (transport coefficients) and can be described by the class of Fluctuation Theorems. These theorems derived for deterministic and stochastic systems allow a statement about the probability distribution of the fluctuations of time-averaged non-equilibrium quantities closely related to entropy production. The idea of M4 is the incorporation of these theorems to modify existing parameterisation schemes, focusing on a stochastic and counter-gradient parameterisation of momentum and heat fluxes which are related to energy dissipation and backscatter.

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Systematic development of an energy consistent stochastic 2 layer QG model

Federica Gugole*,1, Christian Franzke1

We systematically derived a stochastic version of the 2-layer quasi-geostrophic (QG) equations based on its Hamiltonian formulation. The stochastic terms have been introduced in such a way that the total energy is conserved and a parameter $\varepsilon$, depending on the different time scales, has been inserted to introduce time scale separation between the barotropic and the baroclinic modes. The spatial structure of the stochastic noise is determined through dimension reduction techniques. We employ stochastic and deterministic solvers in such a fashion that the resulting numerical model is energy conserving. Our aim is to analyse how the introduction of the stochastic terms can affect and improve the simulation at coarse resolutions. Then we will compare our outcomes with other stochastic discretizations present in the literature. In our presentation we will discuss the results.

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Experimental investigation of Lagrangian coherent structures in stably stratified turbulence

Marius Mihai Neamtu Halic*,1, Markus Holzner1

In turbulent flows, large and long-living coherent structures have been found to dominate the global transport of mass and momentum, presumably because they act as transport barriers. Even more persistent coherent structures have been observed to appear in stratified turbulence with major impact on transport of temperature and heat. Coherent structures thus play a key role in determining flow and transport in many turbulent flows in nature and technology, such as jets, gravity currents or the planetary boundary layer.

An experimental analysis of Lagrangian coherent structures (LCSs) in a stably stratified turbulent flow is presented. The stably stratified turbulent flow, under investigation in this poster, is realized through a laboratory gravity current. For flow velocity measurements, 3D particle tracking velocimetry is employed, which allows to obtain 3D velocity and its derivatives along Lagrangian particle trajectories. To achieve high spatial resolution measurements in a sufficiently large observation domain, a multivolume approach allowing to combine several PTV systems, is employed. For LCSs extraction, we adopt a recently developed objective method based on Lagrangian Averaged Vorticity Deviation (LAVD) theory. In this study, we focus on the influence of the relative strength between the shear and the buoyancy forces on the typical size, orientation, shape, and organization of objectively detected rotational coherent structures.

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Testing linear marginal stability in stratified shear layers

Chris Howland*,1, John Taylor1, Colm Caulfield1

We use two-dimensional direct numerical simulations of Boussinesq stratified shear layers to investigate the influence of the minimum gradient Richardson number $R_i m$ on the early time-evolution of Kelvin–Helmholtz instability to its saturated ‘billow’ state.

Even when the diffusion of the background velocity and density distributions is counter-balanced by artificial body forces to maintain the initial profiles, in the limit as $R_i m \to 1/4$ the perturbation growth rate tends to zero and the saturated perturbation energy becomes small.

These results imply, at least for such canonical inflectional stratified shear flows, that ‘marginally unstable’ flows with $R_i m$ only slightly less than 1/4 are highly unlikely to become ‘turbulent’, in the specific sense of being associated with significantly enhanced dissipation, irreversible mixing, and nontrivial modification of the background distributions without additional externally imposed forcing.

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Critical transitions in geometrically constrained incompressible turbulence

Adrian van Kan*1, Alexandros Alexakis2

Geophysical and astrophysical flows are often subject to geometrical constraints such as thinness in a particular direction. Geometrical constraints strongly affect the nature of flow at high Reynolds numbers $Re$. This is related to the well-known fact that the behaviour of flows at large $Re$ is depends on the dimensionality of the system. In the two-dimensional Navier-Stokes equations, conservation of enstrophy in addition to energy gives rise to an inverse energy cascade, a transfer of energy to the large scales, while in three dimensions, vortex stretching transfers energy to small scales in a direct cascade. For the idealised case of forced incompressible three dimensional flow in a triply-periodic box with dimensions $L \times L \times H$, with spectrally local forcing at $k_f$ at fixed energy injection rate, it has been found that for high $Re$ and small $A = H/L$, a transition occurs when $S = k_f H$ is decreased below $S_c \approx 0.5$, [1–3]. For $S > S_c$, there is three-dimensional turbulence with a purely forward cascade, while for $S < S_c$, an inverse cascade spontaneously emerges. Similar transitions have been found as a function of Rossby number $Ro$ when rotation is added, [4, 5]. The inverse cascade leads to a growth of total energy at large scales. Even in the absence of large scale dissipation mechanism this process saturates at late times leading to the formation of a condensate. In two-dimensional turbulence, the turbulent condensate is well understood, [6], but in the case of thin three-dimensional layers the behaviour of the condensate phase has not yet been investigated.

In this work we study turbulence in thin layers in the condensate state using a large number of direct numerical simulations varying all parameters of the system. We investigate the energy budget in large and small scales as a function of $Re$, $S$ and the aspect ratio $A$.

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It is shown that in a range of $S < S_c$, an effective eddy viscosity-type spectrally non-local transfer of energy is responsible for the saturation of the condensate. For even smaller $S$, the flow is entirely two-dimensionalised and the inverse cascade is balanced by viscosity. Furthermore, close to the transition $S \approx S_c$ we observe complex bi-stable and hysteretical behaviour close and follow the hysteresis curve of the system.

References


Robustness of coherent sets

Anna Klünker*, 1, Kathrin Padberg-Gehle1

Coherent sets are regions in the phase space of a time-dependent dynamical system that do not freely mix with the surrounding regions over some finite time duration. These coherent sets can be identified via transfer operators.

Different sources of uncertainty may influence coherent flow features. We model both deterministic and stochastic perturbations and study the impact in known systems.

Stochastic perturbations are modelled by interpreting the given velocity field as the drift term in a stochastic differential equation (SDE).

Deterministic perturbations like windage are modelled by using a hybrid velocity field. To address influences by inertia we study a simplified Maxey Riley equation.

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On identification of self-similar characteristics in multi-scale flows using advanced multi-scale data analysis methods

Thomas von Larcher*\(^1\)

Advanced multi-scale data analysis techniques, e.g., Wavelets, Shearlets, and low-rank tensor approximation methods, are often suited to attack high-dimensional problems successfully and they allow very compact representation of large data sets. Specifically, the hierarchical Tree-Tucker format and the Tensor Train format emerge as a promising approach for application to data that are concerned with cascade-of-scales problems as, e.g., in turbulent fluid dynamics. Here, we focus on two particular objectives, that is, we aim at capturing self-similar structures that might be hidden in the data and we present the reconstruction capabilities of multi-scale data analysis techniques tested with 3D channel turbulence flow data.

Our study is concerned with the question of whether those methods can support the development of improved understanding and quantitative characterisation of multi-scale behavior of turbulent flows. However, such multi-scale flow structures in highly irregular flows are not commonly aligned with the underlying grid but are translated, stretched, and rotated. The question here is whether multi-scale data analysis methods can support the development of improved understanding of the multi-scale behavior and whether they are an improved starting point in the development of compact storage schemes for solutions of such problems. Our approach is automatically linked with the following questions: (i) Can real data from multi-scale dynamics be approximated or represented by these techniques and how compact are the resulting storage schemes, i.e what compression rate can be achieved at which level of accuracy? (ii) Does the approximated data retain the dynamics? (iii) Are the methods suitable for detecting cascades-of-scales in real data and in turbulence data in particular?

Provided that our tests yield promising results, those quantitative

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features could be helpful in developing a LES closure approach based on and extending the idea of fractal or dynamic SGS models. Therefore, if proved positively, a long-term goal would be the construction of a self-consistent closure for LES of turbulent flows that explicitly exploits the Tensor decomposition approach’s capability of capturing self-similar structures. The approach is validated with respect to compression rate and storage requirement. In tests with synthetic data, it is found that grid-aligned self-similar patterns are well captured, and also the application to non grid-aligned self-similarity yields satisfying results.
Large-scale pattern formation in two-dimensional active suspensions

Moritz Linkmann*,1, Guido Boffetta, Cristina Marchetti, Bruno Eckhardt

The collective effects of microswimmers in suspensions give rise to patterns of vortices at scales much larger than the characteristic size of a microswimmer. For the large-scale dynamics, Navier-Stokes based models driven by small-scale forces have been proposed. Here, we study the properties of a variant of these models in two dimensions, where the collective effects of the microswimmers can couple to the inverse cascade in two-dimensional turbulence. The dynamical and statistical properties of this model show a sharp transition between the formation of a steady-state condensate at the largest resolved length scale in the system and a steady-state inverse transfer which is damped by viscous dissipation before reaching the condensate. The results suggest that large-scale patterns form for sufficiently strong forcing only, in a rather sharp transition.

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Mode interactions in spherical Rayleigh-Bénard convection

Paul Mannix*,1, Jonathan Mestel

The critical Rayleigh number $Ra_c$ for thermally convective instability depends on the wave-length of the disturbance. In an annular spherical domain with separation $d$, there are degenerate points $(Ra_c, d_c)$ at which instability to two different sets of thermal-rolls occurs simultaneously.

This study provides a weakly non-linear analysis of the multiple-bifurcation problem, demonstrating that four distinct coupled amplitude equations govern the non-linear evolution of these interactions. The choice of which can be predicted from the inherent symmetry of the interacting modes. Considering a variety of $\ell : m$ mode interactions at different values of the Prandtl number $\sigma$, it is found that mixed mode solutions can exist only within certain regions of the parameter space. While for special resonant mode interactions a stable-period solution is found at low Prandtl number $\sigma$. In each case the weakly non-linear prediction is verified using direct numerical simulation.

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Convergence of Ginelli’s algorithm for covariant Lyapunov vectors

Florian Noethen*,1

Covariant Lyapunov vectors (CLVs) describe directions of asymptotic growth rates to small linear perturbations of solutions in a dynamical system. They are used to analyze and describe chaotic behavior in theory and applications such as climate sciences.

During the last few years several algorithms to compute CLVs emerged. One of the most popular algorithms was developed by Ginelli. Although there is a partial convergence result for the first half of the algorithm, it is restricted to a special case and exhibits some conceptional difficulties. Our recent advances provide a complete convergence proof in a more general setting allowing even for degenerate Lyapunov spectra.

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Choice of amplitude constraint for optimal perturbations to stratified shear flows

Jeremy Parker*,1, C. P. Caulfield1,2, R. R. Kerswell1

Optimal perturbations to a possibly evolving reference state are used to explore the dynamical system around it. These are optimal in the sense that they maximise some objective functional, subject to a given amplitude constraint. The choice of such a constraint, typically an energy, is not obvious when considering stratified flows. The natural form of the potential energy does not lend itself to being a constraint, and other choices do not represent the energy in a physical way. We examine different possible choices and compare the resulting optimal perturbations for a test problem, namely maximising the time-integrated eddy diffusivity in an evolving, stratified, hyperbolic tangent shear flow, in two dimensions.

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Coherent families in turbulent flows

Martin Plonka*, 1, P. Koltai1

In order to find and study coherent structures in turbulent flows from an evolutionary perspective, i.e., the whole time continuous evolution, we use two different methods. With the focus on Lagrangian coherent structures and applications we use space-time diffusion maps to extract coherent families from trajectory data.

Alternatively we developed a method utilizing an augmented generator approach to analyze and quantify coherent families for a given velocity field without time consuming trajectory integration.

Further building on these methods we try to optimally enhance or destroy coherence over the whole considered time span and expand our methods to more complex settings such as stochastically parametrized systems.

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Synchronization in a wave-driven oscillator: circle map dynamics in the tropical stratosphere

Kylash Rajendran*,1, Irene Moroz1, Peter Read1, Scott Osprey1

The Quasi-Biennial Oscillation (QBO) is a wave-driven east-west wind oscillation in the Earth’s tropical stratosphere. The average period of the wind oscillation is 28 months, but displays significant cycle-to-cycle variability. We present an analysis of this variability of the QBO by considering its theoretical susceptibility to synchronization; that is, the adjustment of the rhythms of the QBO under the influence of a periodic external force. In this case, the external force is taken as the annual variation in the strength of vertical winds in the tropical stratosphere. The response of the QBO to this imposed forcing is explored in detail using a partial differential equation (PDE) model of the QBO. As a result of the nonlinear interaction between the oscillators, the QBO is shown to enter various states of synchronization, including exact frequency locking, discrete multi-cycle periods, and quasiperiodic behaviour. Furthermore, by recasting the governing PDE into the form of a descent rate model, we demonstrate that the dynamics of the QBO period can in fact be described by a simple one-dimensional non-autonomous ordinary differential equation. This simplification greatly reduces the complexity of the model, whilst retaining all the key observed features of synchronization. The simplified model is shown to be closely related to the well-known circle map from dynamical systems theory, and provides a robust mathematical framework within which to interpret observations of synchronization in the stratosphere.

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Exact coherent states and nonlinear dynamics of inclined layer convection

Florian Reetz*,1, Priya Subramanian2, Tobias M. Schneider1

Thermal convection between two horizontal plates, a lower hot plate and an upper cold plate, is well-known to exhibit nonlinear dynamics and chaos. If such a convection cell is inclined against gravity, buoyancy force drives hot and cold fluid up and down the incline leading to a shear flow in the base state and the emergence of new complex dynamics and pattern formation. A prominent convection pattern at intermediate angles between 20 and 70 degrees shows chaotic undulations and local break-up of convection rolls, so called crawling rolls [Daniels et al., 2000]. Crawling rolls are highly nonlinear and emerge far from known instability thresholds which makes theoretical progress difficult.

This poster presents fully nonlinear exact coherent states of inclined layer convection at system parameters where crawling rolls are observed. A numerically simulated phase portrait starting from the unstable base state reveals how the state vector of the system visits the vicinity of three unstable exact coherent states before it terminates on an attracting homoclinic orbit. The transient dynamics are governed by a dynamically unstable periodic orbit which seems to underlie the dynamics of crawling rolls.

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Computing Lagrangian Coherent Structures from time-averaged Geometric Heat Flow

Nathanael Schilling*,1, Alvaro de Diego†,1

An approach to detecting long living structures in turbulent fluids is by looking at Lagrangian Coherent Sets. These describe material subsets that are maximally resistant to diffusion under a time-dependent flow. The total diffusion can be approximated by taking the average of finite time diffusion tensors pulled back to material coordinates. LCS can then be found by computing eigenfunctions of an elliptic variable-coefficient diffusion operator. We describe how to efficiently solve this eigenproblem by suitably adapted Finite Element Methods and show corresponding numerical experiments.

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DYNAMICAL SYSTEMS & TURBULENCE 2018
Turbulence models via geometric generalized Lagrangian mean

Sergiy Vasylkevych*\(^1\)

Combing recently developed geometric generalized Lagrangian mean theory with generalized Taylor hypothesis and isotropy of fluctuations as closure assumptions, we derive equations for the mean flow governed by Burgers, Euler, Euler-Boussinesque, and primitive equations. Averaging Burgers equation yields Camassa-Holm and EPdiff equations as the model for the mean, while in the remaining cases we obtain so-called alpha models corresponding to the parent system.

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Wave interactions and turbulence in an inclined free surface rotating tank experiment

Wenchao Xu*,1, Uwe Harlander†,1

In the present research we experimentally studied the wave interactions in an inclined rotating annulus with a free surface. This is a setup of particular interest since it mimics rotating fluids forced by precession. This type of forcing is relevant to the dynamics of planetary bodies but also in the context of vortex dynamics: a rotating mid-latitude low-pressure system is forced by precession too since it rotates with the Earth.

Particle Image Velocimetry (PIV) was applied for quantitative measurements of the instantaneous structure of the flow. The PIV results revealed that a strong forced Kelvin mode is generated due to the inclination, which has the same frequency as the rotation frequency $\Omega_0$. Through Fourier analysis, a number of other free modes were detected within the frequency range $0 < \omega < 2\Omega_0$. The velocity fields of these modes were reconstructed by using harmonic analysis, thus their wave number was extracted in radial and azimuthal direction to investigate whether the free modes can form resonant triads with the forced mode. In agreement with experimental wave interaction studies using a more classical precession setup, a breakdown of the modes has been observed due to resonance of the forced mode at critical values of the fluid depth. This has recently been investigated numerically for cases where also the free modes become resonant. Our preliminary experiments imply that the flow can become turbulent even when the latter resonance does not hold exactly.

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