Mathematical Developments
in Geophysical Fluid Dynamics

WORKSHOP 2:

Instabilities and transitions in geophysical flows

May 18 to 22, 2026 - IHP, Paris

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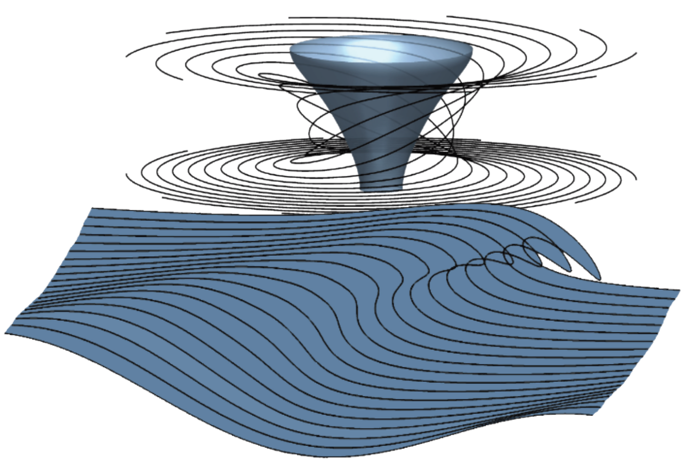

1 Schedule

Monday 18 May

Time	Speaker	*Title*
09:15 - 09:45	*Welcome coffee & registration*	
09:45 - 10:00	Introduction	
10:00 - 10:50	**Stephen Griffies**	***A primer on ocean mesoscale eddy parameterizations for numerical models***
10:50 - 11:20	**Anna Frishman**	*Coexisting fluxes in rotating turbulence*
11:20 - 12:10	**Vlad Vicol**	***Stable Implosions***
12:10 - 13:30	*Lunch*	
13:30 - 14:20	**Stefan Llewellyn Smith**	***Horizontal/vertical convective stability***
14:20 - 14:50	**Julien Guillod**	*Nonuniqueness in fluid models*
14:50 - 15:20	*Break*	
15:20 - 16:20	*(2 min each)*	*Poster presentations*
16:20 - 18:00		*Poster session*

Tuesday 19 May

Time	Speaker	*Title*
09:30 - 10:20	**Peter Constantin**	***Ideal Magnetic Reconnection***
10:20 - 10:50	*Break*	
10:50 - 11:20	**Jincheng Yang**	*Boundary layers and inviscid limits*
11:20 - 12:10	**Peter Korn**	***Arnold's Geometry on Finite Meshes***
12:10 - 13:30	*Group picture, then Lunch*	
13:30 - 14:20	**Emmanuel Grenier**	***Bifurcations of shear flows***
14:20 - 14:50	**Remi Tailleux**	*Diffusive instabilities in seawater*
14:50 - 15:20	*Break*	
15:20 - 16:10	**Celine Guervilly**	***Rotating fingering convection***
16:10 - 16:40	**Lucas Ertzbischoff**	*Asymptotics of inviscid stratified flows*
16:40 - 17:10	**Antoine Venaille**	*Western intensified turbulence*

Wednesday 20 May

Time	Speaker	*Title*
09:30 - 10:20	**Roberta Bianchini**	***Unstable internal waves***
10:20 - 10:50	*Break*	
10:50 - 11:20	**Alexandros Alexakis**	*Cascade transition in geophysical flows*
11:20 - 12:10	**Laszlo Szekelyhidi**	***MHD turbulence and weak solutions***
12:10 - 13:30	*Lunch*	
13:30 - 14:20	**Catherine Sulem**	***Hydroelastic waves***
14:20 - 14:50	**Bruno Andreotti**	*Rythmic patterns: dunes, ripples & more*
14:50 - 15:20	*Break*	
15:20 - 16:10	**Ian Tice**	***Bore wave solutions to Navier-Stokes***
16:10 - 16:40	**Miguel Bustamente**	*Gibbon flow and the d'Alembert's paradox*
16:40 - 17:10	**Mahendra Verma**	*Exact Energy Transfers in Turbulence*

Thursday 21 May

Time	Speaker	Title
09:30 - 10:20	**Keaton Burns**	***Rayleigh-Benard on a logarithmic lattice***
10:20 - 10:50	*Break*	
10:50 - 11:20	**Sam Krupa**	*Solutions to conservation laws unique?*
11:20 - 12:10	**Chongchun Zeng**	***Unstable Manifolds of Euler Equations***
12:10 - 13:30	*Lunch*	
13:30 - 14:20	**Edgar Knobloch**	***Reduced and rescaled equations for RRRBC***
14:20 - 14:50	**Charlotte Perrin**	*Congestion phenomena in fluids*
14:50 - 15:20	*Break*	
15:30 - 16:10	**Miguel Rodrigues**	***On the Instability of Small Stokes Waves***
16:10 - 16:40	**Michael Lebars**	*Instabilities around mesoscale eddies*
16:40 - 17:10	**Louis Philippe Nadeau**	*The Dynamical Landscape of the AMOC*

Friday 22 May

Time	Speaker	Title
09:30 - 10:20	**Colm-cille Caulfield**	***Transition in Stratified Shear Flows***
10:20 - 10:50	*Break*	
10:50 - 11:20	**Nicolas Grisouard**	*Ekman-inertial instability*
11:20 - 12:10	**Nader Masmoudi**	***Long time dynamics 2D Navier-Stokes***
12:10	*Lunch*	

2 List of posters

Dynamic stabilization	Monia Bel Hadj Salah
Fourier phases determine cascades in 2D	Santiago Benavides
The electromotive force in MRI dynamos	Mattias Brynjell-Rahkola
Freely floating cylinder on a 3D fluid	Ewan Contentin
Non-normal amplification in shear flows	Yohann Duguet
Shear-driven Instabilities	Virgin Durepaire
On the shape of condensing steam jets	Nathan Fourcade
Bounds for the Taylor dynamo	Hezekiah Grayer II
Phase transition in plasma turbulence	Pierre Guillon
Structures of 2D Euler steady states	Yupei Huang
GFD instabilities in astrophysical discs	Henrik Latter
Wave turbulence - non linear source term	Louis Milhamont
QG convection on the f-plane	Benjamin Miquel
Topology of rough fluids and plasmas	Javier Peñafiel-Tomás
Onset of Rapid Rotating Dual Convection	Yadagiri Rameshwar
Anisotropic Effects in Magnetoconvection	Hari Ponnamma Rani
Confinement of vorticity on the sphere	Emeric Roulley
A New Wind–Rotation Instability in Shear	Preethi S
Turbulent Compressible Convection	Lekha Sharma
Geomagnetic Core Field Forecasting	Jan Simkanin
Singular solutions of IPM	Jin Tan
Instabilities in an ellipsoidal vortex	Jérémie Vidal
Classification of atmospheric waves	Hao Zhu

3 Oral Presentations

Cascade transition in geophysical flows
Alexandros ALEXAKIS (LPENS, ENS)
I will discuss how a cascade can transition from a forward to an inverse cascade in geophysical flows as a parameter is varied. I will review some of the past results and present some of the most resent results in rotating flows and stratified flows.

Rythmic patterns: dunes, ripples & more
Bruno ANDREOTTI (LPENS)
Periodic patterns spontaneously emerge due to sublimation, erosion/deposition and sediment transport, dissolution, or—when it comes to waves—mechanical deformation of an interface. Starting with sand ripples and dunes, I will thoroughly discuss the various aspects of how these patterns form: linear instability vs pattern coarsening; laminar vs turbulent flow; mixing vs normal stress vs shear stress instability.

Unstable internal waves
Roberta BIANCHINI (Consiglio Nazionale delle Ricerche)
Stably stratified fluids (e.g., oceans and atmosphere) support internal waves that are fundamental to oceanic circulation and atmospheric dynamics. We present the first rigorous proof of instability for small-amplitude internal waves, establishing the existence of an unstable spectrum for the Boussinesq equations linearised about a traveling wave. The analysis combines a Floquet–Bloch decomposition with a variant of Kato's similarity transformation, exploiting the wave's structure. In a specific regime, the resulting growth rates agree with previous theoretical predictions for Triadic Resonant Instability of internal waves.

Rayleigh-Benard on a logarithmic lattice
Keaton BURNS (Massachusetts Institute of Technology)
with Steven Tobias (Univ. Edinburgh), Curtis Saxton (Univ. Leeds), Richard Kerswell (Univ. Cambridge)
Our ability to numerically study turbulent convection is limited by the high cost of direct numerical simulations (DNS) in the regimes relevant to geophysical and astrophysical flows. This motivates the development of alternatives to DNS which enable faster computation by using reduced models of the full dynamics. Here we explore the use of logarithmic Fourier lattices (LFLs) combined with sparse Chebyshev methods to capture extreme dynamic ranges of spatial scales in Rayleigh-Benard and rotating convection. LFL schemes use a Fourier series with logarithmically rather than linearly distributed wavenumbers. We will discuss ongoing work testing different forms of LFL discretizations by examining their ability to reproduce spectra and transport scalings at extreme parameters. This includes formulations with different lattice spacings, triad weightings, and new modifications for the inclusion of coherent structures.

Gibbon flow and the d'Alembert's paradox
Miguel D. BUSTAMANTE (University College Dublin)
with Yinshen Xu (UCD), Tiziana Comito (UCD), Johan Hoffman (KTH), John D. Gibbon (Imperial)
Consider incompressible inviscid flow past an object. D'Alembert (1752) proved that for potential flow, the object experiences no drag force. However, experimental observations find significant drag at high Reynolds numbers, leading to the famous d'Alembert's paradox in fluid mechanics. Prandtl (1904) proposed a milestone solution to this paradox through his boundary layer theory, which attributes drag primarily to the viscous boundary layer. Recently, Hoffman and Johnson (2010) revisited the paradox, bypassing the use of viscosity. In a computational "weak" solution of the 3D Euler equations of flow past a cylinder with slip boundary conditions, they found turbulence to be the primary source of drag. We prove this analytically, showing that Gibbon et al.'s (1999) stagnation-point-like solution of the 3D Euler equations, with appropriate inflow conditions, holds at the rear separation zone. Via a linear instability, nonlinear (stable) streamwise helical vortices form, causing drag.

Transition in Stratified Shear Flows
Colm-cille CAULFIELD (University of Cambridge)
(Vertically) stratified shear flows, where both the background horizontal velocity and buoyancy distribution vary in the vertical (i.e. the direction parallel to gravity) are ubiquitous in geophysical fluid dynamics. A key question is how such flows undergo the transition to turbulence and hence irreversibly mix vigorously. Intuitively, if the buoyancy increases upwards (anti-parallel to gravity), i.e. the fluid is 'statically stable' relative to convection, there should be a competition between the apparently stabilising effect of the buoyancy force and the destabilising effect of shear, quantified classically in terms of a Richardson number, a coupling parameter between the buoyancy and velocity fields. However, transition in stratified shear flows has proved to be significantly more subtle. Behaviour depends on the flow's Reynolds number and Prandtl number, and indeed the turbulence near transition can be qualitatively different in stratified flows and unstratified flows.

Ideal Magnetic Reconnection
Peter CONSTANTIN (Princeton University)
Magnetic fields do not change topology during smooth dynamics of ideal MHD. But topology change does occur in nature. Magnetic resistivity and near singularities have been suggested as a possible explanation. In this talk I will focus on a different explanation, also suggested in the physics literature: reconnection due to magneto-hydrodynamic inertia. I will describe 2D models that exhibit rigorous ideal topology change. The models have global smooth solutions and the reconnection is obtained from merger of a pair of active scalars transported by incompressible velocities they create. Finite time merger without singularities and without resistivity or viscosity is proved rigorously. This is joint work with Zhongtian Hu.

Asymptotics of inviscid stratified flows
Lucas ERTZBISCHOFF (Université Paris Dauphine - PSL)
I will talk about recent mathematical progress on asymptotic regimes for inviscid stratified fluid models, focusing on two topics that remain only partially understood: (i) the long-time dynamics and (ii) the hydrostatic limit. As a guiding example I will use the classical 2d Euler-Boussinesq system. I will try to connect these two questions for this model, highlighting the role of (in)stability issues and important mechanism such as mixing or dispersion.

Coexisting fluxes in rotating turbulence
Anna FRISHMAN (Technion)
with Sebastien Gome
Turbulence is characterized by energy fluxes, whose direction is determined by conservation laws. In 3D rotating turbulence, however, energy is observed to flow simultaneously toward large-scale two-dimensional structures and toward small-scale three-dimensional waves. Using a mean–wave kinetic theory, we derive analytical expressions for these competing bi-directional transfers in the presence of a spontaneously emergent 2D mean flow. We show the direction of the energy transfer is determined by the type of allowed 2D-3D interactions: the mean flow is fed by a sector of modes for which only same-sign-helicity interactions are allowed, while modes which have helicity-mixing interactions extract energy from it. The balance between the two sectors changes as the Rossby- and Reynolds-numbers are varied. We obtain the 2D-3D energy partition as a function of Rossby and Reynolds analytically, in agreement with fully nonlinear simulations, presenting a unified picture across rotation rates.

Bifurcations of shear flows
Emmanuel GRENIER (Chinese Academy of Sciences)
Generic shear flows are unstable for the incompressible Navier-Stokes equation as the viscosity goes to 0 between the so-called lower and upper marginal stability curves. The aim of this talk is to discuss recent results on the bifurcation which occurs near the upper marginal stability curve.

A primer on ocean mesoscale eddy parameterizations for numerical models
Stephen GRIFFIES (IPSL/LOCEAN/CNRS)
This talk summarizes some ongoing math/physics/numerics questions related to tracer mixing and stirring as realized in ocean models, moving from the small-scale turbulence to the large-scale mesoscale eddy stirring. The presentation will be pedagogical in style, and it touches only a few topics with an aim to engage both students and researchers.

Ekman-inertial instability
Nicolas GRISOUARD (University of Toronto)
Ekman-inertial instability (EII) occurs in Ro=O(1) jets when the magnitude of the anticyclonic vertical vorticity exceeds that of the Coriolis parameter, and when surface stress differs from interior viscous stress of the thermal wind shear immediately under the surface. EII is to Ekman spirals what symmetric instability is to internal waves. It can grow explosively fast at first due to its non-normal nature and eventually stabilizes to a growth rate equal to that of classical inertial instability. Because of this fast onset, it can outcompete normal-mode instabilities immediately below the surface. We outline the 1D theory and then show, using constant-density, low-noise, 2D initial value problems, that EII outcompetes inertial instability. In baroclinic, low-noise, 2D initial value problems, EII outcompetes symmetric instability, resulting in distinct patterns in energy extraction from the balanced jet.

Rotating fingering convection
Celine GUERVILLY (Newcastle University)
with Martin Gray, Graeme Sarson
We study double-diffusive convection in the case of an unstable compositional gradient in the presence of a stabilising temperature gradient. Experimental and analytical studies (Hage and Tilgner 2010; Schmitt 2011) have shown that narrow salt fingers (usually encountered in thermohaline convection in “bottom-heavy” layers) can be preferred over large-scale convection in the regime where the stable temperature gradient is much smaller than the destabilising compositional gradient (the “top-heavy” regime). Here, we extend this problem to the context of planetary cores using hydrodynamical numerical simulations in a rotating spherical shell at low Prandtl number. We show that fingering convection can also be preferred over overturning compositional convection for both weak and strong rotation across large regions of parameter

space and the transition between the two regimes of convection is gradual.

Nonuniqueness in fluid models

Julien GUILLOD (Sorbonne Université and ENS Paris)
with Dallas Albritton, Mikhail Korobkov, Xiao Ren, and Vladimír Šverák

It is well known in physics literature, despite almost no mathematical results, that the steady states of fluid model equations are not unique and appear through bifurcations when the Reynolds number increases. After presenting this, the same methodology will be used for time-dependent problems to obtain the non-uniqueness of solutions to Cauchy problems. Numerical non-uniqueness results will be presented for the Navier-Stokes equations in both two and three dimensions. The physical implications will be discussed in particular.

Reduced and rescaled equations for RRRBC

Edgar KNOBLOCH (University of California at Berkeley)
with K. Julien, A. van Kan, B. Miquel, G. Vasil

Geophysical flows are characterized by parameter values that are far outside those that can be studied in the laboratory or via state of the art numerical simulations. I will describe a formal multiscale asymptotic procedure for rapidly rotating convection that leads to a reduced system of equations valid in the limit of vanishing Ekman number. These equations describe four regimes as the Rayleigh number Ra increases: a disordered cellular regime near threshold, a regime of weakly interacting convective Taylor columns at larger Ra, followed for yet larger Ra by a breakdown of the Taylor columns into disordered plumes, and finally by geostrophic turbulence. When scaled using the asymptotic scales, the full equations can be integrated at Ekman numbers six orders of magnitude smaller than the current state of the art, approaching geophysically realistic values for the very first time. The stationary state results converge to the predictions of the asymptotically reduced equations.

Arnold's Geometry on Finite Meshes

Peter KORN (Max Planck Institute for Meteorology, Imperial College London)

Arnold identified ideal fluid motion with geodesics on the group of volume-preserving diffeomorphisms, whose curvature controls hydrodynamic stability. We develop this programme on finite meshes, establishing an approximate finite-dimensional Lie algebra supported by a discrete de Rham complex. This yields well-posed discrete Euler equations that converge to the continuum Euler equations. We derive Arnold's curvature formula and Lorenz's predictability barrier. Finite-dimensional Hopf–Rinow restores geodesic completeness, resolving Shnirelman's obstruction. We connect this to Brenier's relaxed least-action principle, and give a finite-dimensional realisation of the De Lellis–Székélyhidi convex integration scheme, making the construction of wild weak solutions explicit on the mesh. A phase transition emerges as $h0$: local geometry converges while completeness and uniqueness change qualitatively, with curvature providing the geometric link between instability and non-uniqueness.

Solutions to conservation laws unique?

Sam KRUPA (École normale supérieure)
with László Székelyhidi, Jr.

For hyperbolic systems of conservation laws in 1-D, fundamental questions about uniqueness and blow up of weak solutions still remain even for the apparently "simple" systems of two conserved quantities such as isentropic Euler and the p-system. Similarly, in the multi-dimensional case, a longstanding open question has been the uniqueness of weak solutions with initial data corresponding to the compressible vortex sheet. We address all of these questions by using the lens of convex integration, a general method of constructing highly irregular and non-unique solutions to PDEs. Our proofs involve computer-assistance. This talk is based on joint work with László Székelyhidi, Jr.

Instabilities around mesoscale eddies

Michael LE BARS (IRPHE, CNRS)
with Antoine Chauchat (IRPHE), Patrice Meunier (IRPHE), Keaton Burns (MIT)

Our current understanding of ocean mixing remains insufficient to balance the global ocean energy budget, pointing to overlooked local mechanisms. At the edges of mesoscale eddies, horizontal density layering is observed, suggesting enhanced vertical mixing. To investigate its origin, we examine the underlying instabilities. We model this configuration using a solid ellipsoid undergoing differential rotation within a rotating stratified fluid. Combining analytical and experimental approaches, we characterize instabilities across a large range of Rossby, Froude, and Reynolds numbers. Experiments are conducted in a 1 m rotating tank using Particle Image Velocimetry and Schlieren imaging. The base flow is first compared to an exact analytical solution for arbitrary aspect ratios. Observed modes are then compared with a linear stability analysis using the Dedalus solver. We identify in particular viscodiffusive and centrifugal instabilities and assess their contributions to mixing.

Horizontal/vertical convective stability
Stefan LLEWELLYN SMITH (UCSD)
with Michael Le Bars, Clement Audefroy
Motivated by planetary science, we examine the stability of flows with both buoyancy gradients on horizontal boundaries and vertical buoyancy fluxes entering the domain, hence combining aspects of horizontal convection (HC) and Rayleigh–Bénard (RB) convection. Exact steady states exist in the form of shear flows. Unlike the case of RB and classical shear flow stability, the principles of exchange of stability and Squire's theorem no longer hold, so that the marginal modes are no longer two-dimensional with zero frequency. We explore the stability boundary numerically in the horizontal/vertical Rayleigh number/Prandlt number parameter space. Using scaling arguments, we identify different families of modes: RB modes, central shear modes for small Prandtl numbers, boundary-trapped shear modes and 3D baroclinic modes.

Long time dynamics 2D Navier-Stokes
Nader MASMOUDI (NYUAD)
In this talk, we study the long-time behavior of solutions to the two-dimensional Navier-Stokes equations in the presence of Couette flow on the half plane with Navier-slip boundary conditions. We construct the profile that describes the leading order term when time goes to infinity.

The Dynamical Landscape of the AMOC
Louis-Philippe NADEAU (Institut des sciences de la mer de Rimouski)
While AMOC stability is traditionally viewed through simple box models, these models exhibit a diverse range of behaviors dictated by the background climate. These can be classified into two regimes: abrupt tipping points (saddle-node bifurcations) and millennial-scale oscillations (Hopf bifurcations). This presentation reviews the evolution of conceptual models of the AMOC, identifying how mechanisms like advection, diffusion, sea ice, and stratification drive these distinct behaviors. We introduce a minimal, physically based framework that maps the system's full bifurcation space against global temperature and freshwater forcing. This approach offers a unified perspective on AMOC dynamics, demonstrating that warm, present-day climates are prone to saddle-node collapses, whereas cold, glacial-type climates naturally favor limit-cycle oscillations.

Congestion phenomena in fluids
Charlotte PERRIN (CNRS, Institut de Mathématiques de Marseille)
This talk addresses recent developments on fluid models with a maximal density constraint. Such constraints arise in the modeling of congestion effects, with applications to geophysical flows such as dense granular avalanches and sea ice dynamics. I will focus on the main theoretical and numerical difficulties induced by this framework, including strong nonlinear effects, transitions between compressible and incompressible regimes, and the resulting challenges for stable and accurate simulations.

On the Instability of Small Stokes Waves
L. Miguel RODRIGUES (Univ Rennes)
Ziang Jiao, Zhao Yang (Beijing, China), Changzhen Sun (Besançon, France).
We report on a recent proof that all irrotational planar periodic travelling waves of sufficiently small-amplitude are spectrally unstable as solutions to three-dimensional inviscid finite-depth gravity water-waves equations. The associated temporal growth scales sharply with respect to the amplitude of the wave.

Hamiltonian Dysthe equation for hydroelastic waves in a compressed ice sheet
Catherine SULEM (University of Toronto)
with Philippe Guyenne, Adilbek Kairzhan
This study concerns the motion of nonlinear hydroelastic waves along a com- pressed ice sheet lying on top of a two-dimensional fluid of infinite depth. Applying tech- niques of Hamiltonian perturbation theory, a Hamiltonian Dysthe equation is derived for the slowly varying envelope of modulated wavetrains. The derivation is further complicated by the presence of cubic resonances. A Birkhoff normal form transformation is introduced to eliminate non-resonant triads while accommodating resonant ones. Numerical solutions constructed from the Dysthe equation are compared to direct simulations of the full Euler system, and very good agreement is observed.

MHD turbulence and weak solutions
László SZÉKELYHIDI (Max Planck Institute for Mathematics in the Sciences)
with Matteo Giardi
The ideal magnetohydrodynamic system in three space dimensions consists of the incompressible Euler equations coupled to the Faraday system via Ohm's law. This system has a wealth of interesting structure, including three conserved quantities: the total energy, cross-helicity and magnetic helicity. Whilst the former two are analogous to the total kinetic energy for the Euler system, magnetic helicity is known to be more robust and of a different nature. In particular, when studying weak solutions, Onsager-type conditions for all three quantities are known, and are basically on the same level of $1/3$-differentiability as the kinetic energy in the ideal hydrodynamic case for the former two. In contrast, magnetic helicity

does not require any differentiability, only L^3 integrability. In the talk we present and compare some recent constructions of weak solutions and along the way highlight some of the hidden structures in the ideal magnetohydrodynamic system.

Diffusive instabilities in seawater

Remi TAILLEUX (University of Reading)

In two-component seawater, the thermobaric and cabbeling nonlinearities of the equation of state, combined with the disparate molecular diffusivities of salt and heat, give rise to a diverse range of diffusive instabilities. Beyond standard salt finger and diffusive convection instabilities, these include instabilities associated with densification upon mixing. Unlike conventional turbulent diapycnal mixing, which dissipates available potential energy (APE) into background potential energy (BPE), diffusive instabilities can extract energy from the BPE to energise the fluid and provide a source of turbulent kinetic energy. This suggests that in regimes where diffusive instabilities occur, the BPE contains a “latent” form of APE that remains poorly understood. This work reviews the fundamental nature of these processes and identifies the remaining challenges in developing a comprehensive framework for their understanding, drawing on a variety of test cases and examples.

Bore wave solutions to Navier-Stokes

Ian TICE (Carnegie Mellon University)

In this talk we will discuss the construction of two-dimensional traveling bore wave solutions to the free boundary incompressible Navier-Stokes equations for a single finite depth layer of constant density fluid. Our construction is based on a rigorous justification of the formal shallow water limit, which postulates that in a certain scaling regime the full free boundary traveling Navier-Stokes system of PDEs reduces to a governing system of ODEs. We find heteroclinic orbits solving these ODEs and, through a delicate fixed point argument employing the Stokes problem in thin domains and a nonautonomous orbital perturbation theory, use these ODE solutions as the germs from which we build bore PDE solutions for sufficiently shallow layers. This is joint work with Noah Stevenson.

Western intensified turbulence

Antoine VENAILLE (CNRS, ENS de Lyon, Laboratoire de Physique)
with Lennard Miller, Bruno Deremble

We first investigate numerically the vanishing-viscosity limit of a two-dimensional wind-driven ocean model. Instead of forming a large-scale condensate, the flow remains strongly out of equilibrium, organizing into a highly energetic turbulent vortex gas coexisting with western-intensified gyres. When stratification is introduced, coherent Gulf Stream–like jets emerge and can dominate the large-scale flow. We map the phase diagram governing their existence within a two-layer quasi-geostrophic model. Guided by this framework, we present high-resolution simulations with a more comprehensive ocean model, suggesting that increased upper-ocean stratification, an inevitable consequence of global warming, can destabilize the Gulf Stream Extension.

Exact Energy Transfers in Turbulence

Mahendra VERMA (IIT Kanpur)

We developed a mathematical framework called “mode-to-mode energy transfer” to compute energy transfers in fluid flows, in particular turbulence. In this talk, I will describe this general framework and illustrate its application to incompressible and compressible turbulence, turbulent convection, magnetohydrodynamics, dynamo, and quantum turbulence. This is a general framework that enables flux and shell-to-shell energy transfers.

Reference: Energy Transfers in Fluid Flows, Cambridge University Press, 2019

Stable Implosions

Vlad VICOL (New York University)

We exhibit a new class of self-similar implosion solutions for the full compressible Euler equations. For any value of the adiabatic exponent, we construct a sequence of implosion profiles that are smooth before collapse and have an explicit similarity exponent. The first profile in this sequence (the ”ground state”) possesses remarkable stability properties, even outside of spherical symmetry. This is joint work with J. Chen (U Chicago) and S. Shkoller (UC Davis).

Boundary layers and inviscid limits

Jincheng YANG (Johns Hopkins University)
with Alexis Vasseur

I will discuss several recent results on vanishing-viscosity limits for incompressible Navier-Stokes flows near boundaries. I will begin with boundary vorticity estimates and their application to weak inviscid limits near plug flow in a periodic tunnel, giving short-time control of deviations from the shear profile. I will then present unconditional L^2 bounds on boundary layer separation between Leray-Hopf Navier-Stokes solutions and smooth Euler flows in bounded domains. Finally, I will discuss joint work on non-characteristic boundaries, where one can quantify energy dissipation and enstrophy production near outflow in terms of the boundary mismatch between Navier-Stokes and Euler flows.

Unstable Manifolds of Euler Equations
Chongchun ZENG (Georgia Institute of Technology)
Zhiwu Lin and Yanbo Wang
Consider a spectrally unstable steady state $(\rho_0(x), v_0(x))$ of the incompressible stratified Euler equation in certain d-dim domain Ω. Assuming the linearized equation satisfies a linear exponential dichotomy with a reasonably large spectral gap relative to the maximal Lyapunov exponent of $v_0(x)$, we construct a local unstable manifold of (ρ_0, v_0). The proof is based on the Lyapunov-Perron integral equation method after the Euler equation is reformulated as an ODE on the infinite dimensional manifold of volume-preserving Lagrangian maps where the density is treated as a parameter. Applications to steady states in two space dimensions are also discussed.

4 Posters

Dynamic stabilization
Monia BEL HADJ SALAH (Monastir, Tunisia)
Dynamic stabilization of star-shaped network of strings with a dynamical interior mass. In this work, we propose a new control design that systematically integrates both higher-order damping at the boundary and lower-order nodal damping at the interior mass for a star sharped network of strings system. Our framework preserves linearity and continuity in the feedback laws, enabling a rigorous spectral analysis and ensuring exponential stability under specific conditions.

Fourier phases determine cascades in 2D
Santiago BENAVIDES (University of Edinburgh)
with Miguel Bustamante
Despite their importance in turbulence theory, a unifying and predictive dynamical mechanism determining the direction of turbulent cascades is lacking. In this work, we demonstrate how the complex phases of the Fourier transform of the velocity field determine the direction of the cascades in two-dimensional turbulence, thereby providing a major step in the search for such a unifying and predictive mechanism. To do so, we develop a closure for the dynamics of a triad phase, the sum of the phases of three modes forming a triad, based on the observation that neighboring triad phases are weakly correlated. The resulting stochastic model for triad phase dynamics can be solved analytically, providing an expression for the triad phase probability distribution function (PDF). From the triad phase PDF we develop a novel closure of the energy equation. Finally, we prove that the cascade directions are determined by our model without any free parameters, knowing only the energy spectrum.

The electromotive force in MRI dynamos
Mattias BRYNJELL-RAHKOLA (Department of Applied Mathematics and Theoretical Physics, University of Cambridge)
with Gordon I. Ogilvie
In zero-net flux accretion discs, magnetic fields arise through dynamo activity. In a common prototype for such processes, a toroidal field is induced from a weak poloidal field by differential rotation, and the poloidal field is regenerated from the toroidal field by the electromotive force (EMF). A major theoretical challenge is to describe the latter feedback provided by the EMF, which traditionally has been treated using kinematic mean-field theory. In this work, a dynamical systems perspective is adopted where the dynamo is interpreted in terms of self-sustaining processes (SSPs) known to characterise lower branch states in hydrodynamics. In that view, the EMF originates from three-dimensional waves due to the magnetorotational instability (MRI) on a neutrally stable background. During the talk, details of the EMF will be discussed. Specifically, its relation to Alfvén resonant layers will be outlined, which assume a role analogous to critical layers in hydrodynamics.

Freely floating cylinder on a 3D fluid
Ewan CONTENTIN (IRMAR)
with Geoffrey Beck, Ludovic Martaud
We have an interest on a freely floating cylinder on a 3D fluid governed by the Boussinesq equations in the case of the axisymmetric without swirl case. After having taking care of reformuling the model, we prove local well-posedness results. Afterwards we focus on a particular case where the cylinder is dropped without any speed in a fluid at rest, in the linear regime. In such a case we are able to describe the behavior of the motion of the solid in a large time scale and to perform numerical simulations.

Non-normal amplification in shear flows
Yohann DUGUET (LISN-CNRS, Université Paris Saclay)
with Joris Labarbe, Florence Marcotte, Benjamin Favier
Horizontally sheared flows between two solid walls, where the stratification is orthogonal to the shear, are known to support hydrodynamic instabilities involving unstable eigenmodes. Such instabilities are commonly thought as predecessors of the turbulent regime. In contrast to this classical normal mode approach, we investigate the possible amplification of disturbances by external (additive) forcing using linear resolvent analysis. This approach, especially relevant in experimental contexts, allows to take into account non-normal amplification of the background noise. It predicts, depending on the Reynolds and the Richardson number, the possible occurence of non-trivial coherent structures in the flow even when the base flow is linearly stable. The present study focuses on the examples of plane Couette flow, between two sliding plates, and plane Poiseuille flow driven by a pressure gradient.

Shear-driven Instabilities
Virgin DUREPAIRE (Observatoire de Paris — LIRA)
with L. Petitdemange, K. Belkacem, A. Guseva, L. Manchon
We examine magnetohydrodynamic instabilities in rotating, stratified shear flows, with applications to angular-momentum transport and magnetic-field evolution in stellar radiative zones. We focus on shear-driven instabilities, namely the Goldreich–Schubert–Fricke (GSF) instability and the magnetorotational instability (MRI). A local linear stability analysis is performed using a numerical approach that extends beyond classical limits and incorporates stabilizing effects such as stratification and magnetic tension, allowing access to realistic parameter regimes. These results are validated through a global mode analysis in a Taylor–Couette configuration. We derive a new criterion for the magnetised GSF (MGSF) instability and clarify the transition from MRI to MGSF as stabilizing effects progressively restrict the unstable domain. Finally, we illustrate the relevance of these results using models of subgiants and young red giants.

On the shape of condensing steam jets
Nathan FOURCADE (Laboratoire de Physique de L'Ecole Normale Supérieure)
with Bruno Andreotti, Philippe Claudin
Droplet-laden cloud dynamics emerge from phase transitions coupled with turbulent mixing. Combining laboratory experiments and mean-field theory, we establish scaling laws for steam-injected clouds in cool, dry air with condensation nuclei. Two asymptotic regimes arise: a jet-dominated regime, where cloud dimensions scale with injector radius, and a buoyancy-driven plume regime, where size follows a $\dot{m}^{2/5}$ scaling. Our mean-field analysis, based on the simplifying assumption that inter-droplet air remains humidity-saturated, successfully predicts cloud persistence governed by ambient enthalpy-humidity mixing. These findings bridge microphysical processes and macroscale dynamics, offering a quantitative framework for atmospheric cloud evolution.

Bounds for the Taylor dynamo
Hezekiah GRAYER II (Princeton University)
with Ali Arslan
Convection of electrically conductive fluid in the Earth's core is the proposed mechanism generating the geomagnetic field, yet our understanding of the structure of the geodynamo is largely incomplete. Classical antidynamo theorems restrict the geodynamo qualitatively and quantitatively: for dynamo action, the fluid velocity must be three-dimensional and its complexity is lower bounded via functional inequalities. Through an analysis of J.B. Taylor's magnetohydrodynamic equations for the Earth's dynamo, we establish new functional inequalities for the gradients of the temperature field necessary for dynamo action in a nonlinear regime. In the plane layer geometry, we prove explicit lower bounds on the complexity of convection in a working Taylor dynamo. From our bounds, implications from rotating and magneto-convection theory are derived.

Phase transition in plasma turbulence
Pierre GUILLON (Laboratoire de Physique des Plasmas, Ecole polytechnique)
with Özgür Gürcan
The Hasegawa-Wakatani (HW) system is the minimal non-trivial model for instability-driven tokamak turbulence, which exhibits the formation of zonal flows (ZFs) through flow self-organisation. In particular, it exhibits a subcritical bifurcation for the ZFs, between 2D turbulence and a quasi-1D state dominated by steady ZFs, as its linear parameters are varied. The bifurcation is explored in some detail, and presented as analogous to a phase transition between a "hot" disordered state, and a “colder”, one-dimensionalised, organised state. Defining the fraction of zonal energy as the order parameter, and the ratio of linear parameters as the control parameter, a sharp transition is observed that moreover exhibits a hysteresis loop. The hysteresis is interpreted as a consequence of ZFs stabilising the system once they are formed, and requiring some energy akin to latent heat in order to collapse. The transition is also reproduced in a system reduced to a few Fourier modes.

Structures of 2D Euler steady states
Yupei HUANG (Imperial College London)
The topology of generic steady states of the 2D Euler equations is closely related to long-time dynamics. A fundamental

link comes from the semilinear elliptic equations naturally associated with steady Euler flows. In this talk, I will discuss this link from both rigidity and flexibility viewpoints, focusing on simply connected domains.

GFD instabilities in astrophysical discs

Henrik LATTER (DAMTP, University of Cambridge)

Being controlled by the same underlying physics as in geophysical and terrestrial fluid dynamics: rotation, shear, stratification, and (imperfectly) entrained particles, geophysical flows and astrophysical discs (especially those around newborn stars) share many hydrodynamic instabilities, particularly those of a double-diffusive nature. And while in both contexts there is the same tendency to self-organise into coherent structures (staircases, vortices, etc.) and/or generate wave turbulence, their saturation often take different routes due, in part, to their different geometric constraints. This talk will review the points of agreement and contrast between geophysical instabilities and their astrophysical disc cousins, thereby hopefully better illuminating their physical underpinnings in both settings.

Wave turbulence - non linear source term

Louis MILHAMONT (Sorbonne Université - LATMOS)
with ORUBA Ludivine, DORMY Emmanuel, LACAVE Christophe

In third-generation spectral wave models, the nonlinear interaction term is as important as the source and dissipation terms. It controls how energy is redistributed across the spectrum and largely determines the spectral shape. The exact expression, derived by Klaus Hasselmann in the 1960s as a Boltzmann-type integral, is computationally expensive and long considered impractical for operational use. As a result, most models rely on the Discrete Interaction Approximation (DIA), which is efficient but relatively crude. Recent progress based on the GQM formalism has shown that the exact term can be evaluated efficiently with optimized quadrature methods. Building on this, we propose a new approach that computes the nonlinear source term with improved treatment of singularities and higher accuracy, while remaining computationally feasible for practical wave modeling.

QG convection on the f-plane

Benjamin MIQUEL (CNRS, Ecole Centrale Lyon)
with A. Ellison, M. Calkins, K. Julien, E. Knobloch

Planetary cores and the subsurface oceans of icy moons are stirred by quasi-geostrophic turbulent convection. The transport (of heat, momentum, etc.) by the flow vary regionally with the colatitude, which coincides with the tilt angle between gravity and rotation. Here, we analyse rapidly rotating Rayleigh-Benard convection in a local model: the tilted f-plane. Employing non-orthogonal coordinates, we obtain a natural formulation for geostrophy and a set of governing equations for the non-hydrostatic quasi-geostrophic dynamics on the tilted f-plane (fNHQGE), valid in the asymptotic limit of rapid rotation. We conduct a systematic parametric study by varying the Rayleigh number and the tilt angle. As the tilt increases, the barotropic condensate transitions from large scale vortices (near the pole) to East-West jets (near the equator), with bistability at intermediate latitudes. Concomitantly, both heat transport and the vertical kinetic energy decrease monotonically with colatitude

Topology of rough fluids and plasmas

Javier PEÑAFIEL-TOMÁS (ICMAT)
with Alberto Enciso, Daniel Peralta-Salas

In this talk we explore the role of topology in low-regularity fields describing fluids and plasmas. We begin by showing that, unlike classical solutions, weak solutions of the steady Euler equations can exhibit any streamline topology. This is achieved through a novel convex integration scheme that preserves the topology of the field throughout the construction. As an application, this provides counterexamples in a weak sense to Grad's conjecture on the axisymmetry of certain plasma equilibria. In the second part of the talk, we discuss the construction of dissipative solutions of ideal MHD with nonzero helicity. Using a new approach that respects the underlying geometrical structure of the equations, we provide the first example of Hölder continuous solutions in which one quantity is dissipated while another is conserved, even in the absence of symmetry.

Onset of Rapid Rotating Dual Convection

Yadagiri RAMESHWAR (Department of Mathematics, University College of Science, Osmania University, Hyderabad. India.)
with Hari Ponnamma Rani, Sergey Vladimirovich Starchenko

The stability of thermal–compositional convection in a rapidly rotating plane layer with stress-free boundaries and spatial anisotropy is investigated. Linear stability analysis yields a fourth-degree characteristic polynomial, and the fastest growing modes are identified through critical ratios of thermal to compositional dissipation relevant to Earth's core dynamics. Near the onset of stationary convection, weakly nonlinear analysis reveals secondary instabilities, including Eckhaus instability and spatiotemporal chaos. The linear amplitude growth is governed by the interaction of anisotropy, thermal–compositional balance, and dissipation mechanisms. Evolution from noisy initial states to saturated roll patterns with isolated defects is described using the Ginzburg–Landau framework. The influence of coefficients in the Landau–Ginzburg equation is examined across different parameter regimes and compared with theoretical predictions reported in the literature.

Anisotropic Effects in Magnetoconvection

Hari Ponnamma RANI (Department of Mathematics, National Institute of Technology Warangal)
with Krishnendu Nayak, Yadagiri Rameshwar

The effect of anisotropic thermal diffusion on rotating magnetoconvection relevant to geophysical and astrophysical environments has been investigated. The linear stability analysis performed using normal mode methods shows that the onset of stationary and oscillatory Rayleigh-Bénard convection depends on the anisotropy parameter and its interaction with the rate of rotation and strength of magnetic field. To explore the weakly nonlinear, 2D anisotropic complex Ginzburg-Landau equation is derived using multiple-scale analysis, and Benjamin-Feir stability analysis shows that unstable regimes produce amplitude defects, localized structures, and phase turbulence, while stable regimes support coherent traveling waves. Direct numerical simulations further confirm transitions between turbulent, spiral, and chaotic regimes. The results establish anisotropy as a key control parameter governing stability, pattern selection, and nonlinear dynamics in rotating magnetohydrodynamic convection.

Confinement of vorticity on the sphere

Emeric ROULLEY (Università degli Studi di Milano)
with Martin Donati

We present the point vortex dynamics for the Euler equations on the rotating sphere which corresponds to the evolution of absolute vorticity concentrated on several points. We show the improbability of collisions for point-vortices. Then, we study the confinement problem of generic absolute vorticity initially concentrated around a point vortex configuration. More precisely, we find near generic configurations a confinement time logarithmic in the size of the initial support. This time is in general optimal but for some special configuration can be refined into a power-law long confinement.

A New Wind–Rotation Instability in Shear

Preethi S (Indian Institute of Technology Hyderabad)

We investigate the linear stability of a shear flow driven by surface wind stress and rotation at the lower boundary, as a minimal model for wind-driven oceanic flows under Earth's rotation. The resulting eigenvalue problem is solved using a pseudospectral collocation method, together with a longwave asymptotic analysis.

Our computations reveal a previously unreported longwave instability that appears for nonzero rotational Reynolds number. The most unstable disturbance occurs at the lowest critical parameters and corresponds to a spanwise longwave mode with vanishing streamwise wavenumber. The asymptotic theory captures this instability mechanism and shows excellent quantitative agreement with the full numerical results.

These results demonstrate a new instability arising from the combined action of wind shear stress and rotation, and suggest a potentially important mechanism for large-scale dynamics in wind-driven oceanic shear flows.

Turbulent Compressible Convection

Lekha SHARMA (Indian Institute of Technology Kanpur, India)
with Mayank Pathak, Harshit Tiwari, and Mahendra K. Verma

We present a comprehensive study of turbulent compressible convection using two-dimensional (2D) and three-dimensional (3D) simulations for Prandtl numbers (Pr) in the range (0.01, 100) and Rayleigh numbers (Ra) in the range $(10^7,\ 10^9)$. Global heat transport, quantified by the Nusselt number, shows distinct scaling in low- and high-Pr regimes, while the Reynolds number displays strong Pr-dependence in both 2D and 3D. Thermal and viscous boundary layers exhibit persistent top–bottom asymmetry, with thicker layers near the top boundary. Beyond global measures, we analyze local convective heat transport through statistics of vertical heat fluxes. Positive and negative flux contributions are nearly equal, with their difference decaying as $Ra^{-0.20}$, yielding the classical scaling $Nu \sim Ra^{0.30}$ for all Pr. The flux distributions are asymmetric, with longer tails for positive fluxes, which progressively shrink with increasing Ra and Pr.

Geomagnetic Core Field Forecasting

Jan SIMKANIN (Institute of Fluid Dynamics, HZDR, Bautzner Landstr. 400, Dresden-Rossendorf, Germany)
with Martin Rother, Andre Giesecke, Ingo Michaelis, Monika Korte, Frank Stefani

The GEOMAGFOR project aims to explore the potential of AI-based methods to improve geomagnetic core field forecasting on both short and long timescales. For the short term, up to a decade, a particular focus lies on enhancing the accuracy of the IGRF and its predictive capabilities (GFZ Potsdam team). In parallel, the project applies physics-informed artificial intelligence techniques to develop more realistic models of geomagnetic reversals and excursions (HZDR team). At GFZ, we have implemented ML tools to test the predictability of geomagnetic core field spherical harmonic coefficients for short-term forecasts. At HZDR, a two-dimensional α^2-dynamo model implemented in the Dedalus framework has been developed and parameterised by the radial and meridional distribution of the α-effect. Building on this model, PINNs are applied to solve the inverse problem of reconstructing the dynamical evolution of excursions and reversals from paleomagnetic data. We present our findings.

Singular solutions of IPM

Jin TAN (The Chinese University of Hong Kong)
with Charles Collot, Christophe Prange

We consider a special class of infinite energy solutions to the inviscid incompressible porous medium equations (IPM), introduced in Castro-Córdoba-Gancedo-Orive. The (IPM) equations then reduce to a one-dimensional nonlocal nonlinear equation, for which an explicit self-similar blow-up solution is found. We show the stability of this explicit blow-up solution by smooth enough perturbations, and identity a sharp regularity threshold below which it is unstable.

Instabilities in an ellipsoidal vortex

Jérémie VIDAL (CNRS, ENS de Lyon, Univ. Lyon 1)

In geophysics and astrophysics, rotating stratified flows often exhibit large-scale, nearly isolated vortices (e.g., the Great Red Spot on Jupiter). While previous models have explained why these vortices maintain nearly lenticular shapes over time, it remains unclear why they are not usually motionless within the bulk. To address this question, I explore the stability of large-scale pancake-like vortices using an idealised model, consisting of a fluid-filled ellipsoid with a uniform vorticity, a linear density stratification, and a background Coriolis force. Building upon a recent wave description of this model (Vidal & Colin de Verdière, 2024, PRSA), I present a global stability analysis. The latter reveals that that most anticyclonic vortices are unstable to three-dimensional, elliptical-like instabilities within the low-Rossby regime. Finally, I discuss these results in the context of geophysical and astrophysical applications.

Classification of atmospheric waves

Hao ZHU (Nanjing University)

with Adrian Constantin, Zhiwu Lin

We classify within the quasi-geostrophic framework all types of traveling waves in zonal bands of the planetary atmosphere at cloud level according to their wave speeds. This classification pertains to waves of all amplitudes, going beyond the small-amplitude perturbative regime. It provides a structurally robust criterion for determining which traveling-wave profiles are dynamically possible and we show that each wave classification type was observed on Jupiter or Saturn. Building on this classification, we also investigate the related rigidity issue for large-amplitude traveling waves and waves propagating near shear flows. Our study offers a unified quantitative characterization of the intrinsic constraints for traveling waves in the quasi-geostrophic regime of planetary atmospheric flow.

5 Sponsors