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Waves, Instabilities and Turbulence in Geophysical and Astrophysical Flows

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Book of Abstracts

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Effect of background mean flow on PSI of internal wave beams

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An asymptotic model is developed for the parametric subharmonic instability (PSI) of finite-width nearly monochromatic internal gravity wave beams in the presence of a background constant horizontal mean flow. The mean flow is assumed to be small so that its advection effect on the perturbations is as important as dispersion, triad nonlinearity and viscous dissipation. In this 'distinguished limit', a necessary condition for PSI is that perturbations travel in opposite directions across the beam. This constraint stabilizes very short-scale perturbations; as a result, it is possible for a small amount of mean flow to weaken PSI dramatically. The effect of mean flow on near-inertial PSI of gravity-inertia wave beams in a rotating stratified fluid is also discussed.

The dynamical tide in density staircases

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Layered semi-convection could operate in giant planets, potentially explaining Saturn's luminosity excess and playing a role in causing the abnormally large radii of some hot Jupiters. In giant planet interiors, it could take the form of density staircases, which are characterised by a succession of convective layers separated by thin stably stratified interfaces. Those density staircases are also observed in some oceans on Earth, where they are referred to as thermohaline staircases. The efficiency of tidal dissipation is known to depend strongly on the planetary internal structure. It is crucial to improve our understanding of the mechanisms driving this dissipation, since it has important consequences to predict the long-term evolution of any planetary system. In this work, our goal is to study the resulting tidal dissipation when internal waves are excited by other bodies (such as the moons of giant planets) in a region of layered semi-convection. We find that the rates of tidal dissipation can be enhanced in a region of layered semi-convection compared to a uniformly convective medium, where the latter corresponds with the usual assumption adopted in giant planet interior models. In particular, a region of layered semi-convection possesses a richer set of resonances, allowing enhanced dissipation for a wider range of tidal frequencies. Thus, layered semi-convection could contribute towards explaining the high tidal dissipation rates observed in Jupiter and Saturn, which have not yet been explained by theory. Further work is required to explore the efficiency of this mechanism in global models.

Studying internal gravity wave turbulence by 2d stratified flow simulations with FluidSim

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The statistics of temperature and velocity measurements in the oceans are commonly interpreted as the signature of a field of interacting internal gravity waves. However, such regime of internal gravity wave turbulence for oceanic-like parameters (very strong stratification and very large Reynolds numbers) has not been reproduced and studied, neither with laboratory experiment nor with numerical simulations.

We present a numerical study of bidimensional stratified turbulence (confined over a periodic vertical 2d space) forced in wave modes. Our motivation is to check if it is possible to obtain a regime of (weak) wave turbulence with internal gravity waves sustaining a downscale energy cascade.

In stratified turbulence, the flow is usually composed of horizontal divergence and of vertical vorticity, which does not correspond to linear waves. If the goal is to obtain and characterize internal wave turbulence, the interaction of these oscillating and non-oscillating modes is an issue. By confining the flow in a 2d space, one can get rid of the vertical vorticity and one should be able to obtain pure wave turbulence. The shape and the time coherence of the forcing is also carefully chosen to force a field of intermediate-scale waves, so that upscale or downscale cascade could develop. Only small-scale dissipation is used since our aim is to obtain a regime associated with a downscale energy cascade, which could explain oceanic measurements.

We will present the different regimes that can be obtained with such clean numerical setup, with a particular interest in the cases corresponding to the oceanic-like parameters reached at very large resolution. The dynamics of the cascade will be analysed with spectral energy budget and spatio-temporal spectra.

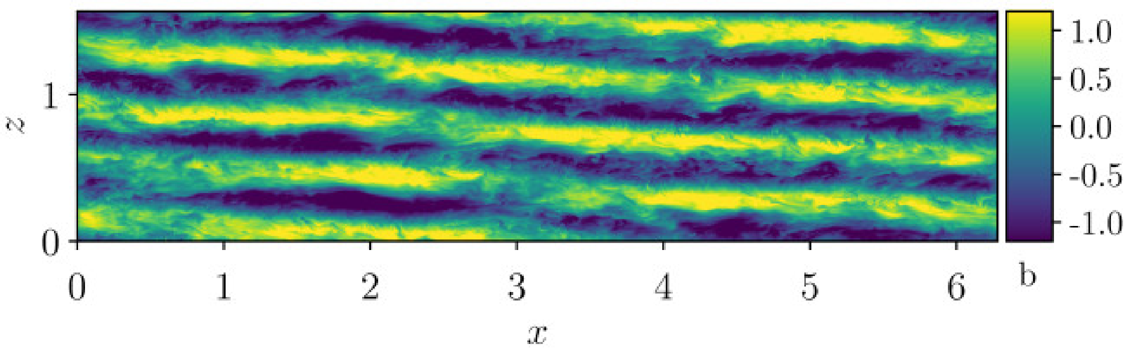

Figure 1: Snapshot of the buoyancy field for a moderately stratified flow.

We will also present FluidSim, the open-source collaborative computational fluid dynamics package used for this study.

Global Climate Modeling of Saturn's stratosphere

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The Cassini spacecraft allowed a detailed characterization of Saturn's stratosphere and its seasonal variability. In particular, infrared sounding on board Cassini revealed an equatorial oscillation of stratospheric temperature, associated with a vertical structure of winds similar to the Earths Quasi-Biennial Oscillation, as well as a possible inter-hemispheric transport of stratospheric hydrocarbons reminiscent of the transport trace species by the wave-driven Brewer-Dobson circulation on Earth.
We have developed a General Climate Model for Saturn, to better understand Saturn's atmospheric circulation. It employs the new DYNAMICO icosaedral hydrodynamical core which allows us to perform simulations at an horizontal resolution of 1/2° in longitude/latitude. Such a high resolution is necessary to start resolving hydrodynamical instabilities and eddies forcing on planetary-scale dynamics. This Saturn GCM was recently used to study the tropospheric dynamics, addressing topics such as tropospheric jet formation, evolution and stability, and planetary wave activity. In the present study, we performed new simulations with the model top extended to 1 μbar in order to investigate Saturns stratospheric circulations.

Firstly, the equatorial zonal jet displays a strong vertical shear with jets stacked on the vertical. It also undergoes episodes of very fast downward propagation of the zonal wind extrema and temperature. This pattern is similar to a QBO-like oscillation, but the amplitude and period do not match the observations. Secondly, between the bottom of the stratosphere (40 mbar) to the model top, our simulations exhibit an other oscillation. It is a tropical (at 20°N and 20°S) strong oscillation in opposition of eastward and westward winds with annual period.

We will consider the residual meridional circulation in the stratosphere and analysis of planetary-scale waves activity to explain the diffenrent oscillations. We have two possibilities inspired by Earth's atmospheric modeling to improve the physical forcings of the QBO-like oscillation. We plan to add either a stochastic gravity wave drag parametrization or a thermal plume parametrization to our GCM. Both are expected to produce a more realistic wave spectrum, which strongly impacts the simulation of the equatorial oscillation and the downward propagation of winds.

Angular momentum transport and jet formation by the GSF instability in differentially rotating stellar radiation zones

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We will present an investigation into the nonlinear evolution of the Goldreich-Schubert-Fricke (GSF) instability in differentially rotating radiation zones. This instability may be a key player in transporting angular momentum in stars and giant planets, and potentially also in astrophysical discs, but its nonlinear evolution remains mostly unexplored. We will present numerical simulations using both a local Cartesian Boussinesq model in a modified shearing box and a model with stress-free, impenetrable, radial boundaries.

At the equator, the linear and nonlinear evolution of the axisymmetric instability is formally equivalent to the salt fingering instability. This is no longer the case in three dimensions, but we find that the instability primarily behaves nonlinearly in a similar way to salt fingering. Axisymmetric simulations – and those in three dimensions in domains with short dimensions along the local azimuthal direction – quickly develop strong jets along the rotation axis, which inhibit the instability and lead to predator-prey-like temporal dynamics. In three-dimensions, the instability initially produces homogeneous turbulence and enhanced angular momentum transport, before forming jets on a much longer timescale.

The instability at a general latitude is found to behave very differently to the case at the equator. In particular, it leads to the nonlinear development of strong zonal jets ("layering" in the angular momentum), and these jets can considerably enhance angular momentum transport. The jets are, in general, tilted with respect to the local gravity by an angle that corresponds initially with that of the linear modes, but which evolves with time and depends on the strength of the flow. The instability transports angular momentum much more efficiently (by several orders of magnitude) than it does at the equator.

Finally, we will present a simple theory for nonlinear saturation of the GSF instability and its resulting angular momentum transport. We estimate that the GSF instability could contribute towards explaining the missing angular momentum transport required in red giant and sub-giant stars, and it could play a role in the long-term evolution of the solar Tachocline.

Dynamics of gas, dust and planets in protoplanetary discs

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Protoplanetary discs are discs of gas and dust surrounding newly formed stars. They are the initial conditions for the formation and evolution of planetary systems. They have been the subject of intense observational scrutiny, and we will first review observational constraints on the structure of protoplanetary discs (shape, size, mass etc.), their lifetime, how much they accrete onto their stellar host. These will motivate the core of this course, which aims to give a practical overview of the physical processes, and related (magneto-)hydrodynamical instabilities when relevant, that control the dynamics of the gas and dust in protoplanetary discs. On the instabilities menu: the magneto-rotational instability, the gravitational instability, hydrodynamical vortex-forming instabilities, and the streaming instability. Interactions between protoplanetary discs and the planets that they form will also be described. We will discuss how relevant these processes are to drive the evolution of protoplanetary discs, and to account for features observed in the discs emission (spirals, vortices, rings).

Modeling eddy-driven jets streams on Jupiter

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Jupiter's tropospheric dynamics is characterised by the presence, among others, of about 30 jet streams whose speeds ranged between 10 and 150 m s^{-1}. Those jets are alternately eastward and westward and delimit bands of cyclonic (belts) and anticyclonic (zones) meridional wind shear. It is assumed that structure is the result of an inverse cascade of energy from small scale instabilities to large scale due to the fast rotation rate of Jupiter.

During my PhD thesis, I will try to explain and understand physical processes which underlie this structure. For that, I use a General Circulation Model (GCM) which is composed of a dynamical core and some physical parametrizations. The dynamical core is DYNAMICO. It solves the atmospheric primitive equations on an icosahedral grid to ensure good energy and momentum conservation as good scalability properties for massively parallel computing. Indeed, high resolution is needed to resolve the small scale cascading instabilities. Parametrizations include mainly radiative transfer but also vertical diffusion, constant internal heat flux and a simple convective adjustment.

In 0.5 degree resolution simulations, 13 jets alternately eastward and westward emerge and their speeds have the good order of magnitude. We can show that they are the result of an inverse cascade of energy from baroclinic instabilities. However, jets are too few numerous. Moreover, baroclinic instabilities at the jet altitude are inconsistent with observations suggesting a near zero temperature gradient at 1 bar pressure level. That's why I am investigating the convection as another source of instabilities. I will discuss those first results as well as convection influence on large scale circulation during the summer school.

Oscillatory instability of a fluid in two-phase equilibrium in a porous medium

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Studying the instability of a liquid layer embedded in a porous medium heated on the bottom and cooled down on the top dates back to the middle of the 20th century.[1].

Shortly after, a new interest was cast on this system : the case where the bottom temperature goes beyond the ebullition point of the liquid. In low permeability media, a two-phase zone arises under the liquid zone (thanks to surface tension). This two-phase zone is composed of a mixture of the fluid under liquid and gaseous forms.

The dynamic of the convection in this system has been studied in great details. Among many articles, the numerical analysis of [2] shows the existence of four states : the fluid exists in one or two separate phases, and the thermal transfer regime is either conductive or convective. Two dimensionless numbers are used to characterize the system : the Rayleigh number Ra and the dimensionless heat flux Q_b.

A peculiar secondary instability of this system was initially observed by [3]. In the presence of a liquid zone overlying a two-phase zone, the separation between these zones can spontaneously start oscillating. This movement takes place with an oscillation of the temperature field in the liquid zone, and with periodic admission and expulsion of fluid at the top (which is, in this case, permeable).

The motivations for studying such a phenomenon are numerous : firstly, this system acts as a toy model in geophysics, and allows the description of hydrothermal complexes (volcanic lake) [4]. Secondly, this problem encompasses a great number of physical features, as it mixes thermodynamics, fluid mechanics and non-linear dynamics. The coupling between this secondary instability and the enhancement of the thermal transfer is a major challenge for the physicist.

Two complementary experimental devices are used in this study : an experimental cell built in opaque polymer isolated in the vacuum, the measurements being realised through thermistances spaced unequally in the porous medium ; and an experimental cell in glass, allowing for infrared camera measurements of the boundary temperature field. In both cases, the liquid level on the top is monitored through a capacitive sensor.

On both the theoretical (supported by numerical computations) and experimental side, we are interested in the linear and non-linear dynamics of this instability : which parameters regime triggers it? What are the scaling laws associated with the oscillation amplitude and frequency? Does this system exhibit hysteretical behaviour? How does the Nusselt number evolve in parameter space?

References

[1] E. R. Lapwood, *Convection of a fluid in a porous medium.* Mathematical Proceedings of the Cambridge Philosophical Society, Cambridge University Press, 508521, 1948.

[2] P.S. Ramesh, K.E. Torrance, *Stability of boiling in porous media*, International Journal of Heat and Mass Transfer, Volume 33, Issue 9, 1990, Pages 1895-1908.

[3] Bau, Haim & K.E. Torrance. *Boiling in Low-permeability Porous Materials.* International Journal of Heat and Mass Transfer 25. 45-55. 1982

[4] Vandemeulebrouck, J., D. Stemmelen, T. Hurst, and J. Grangeon, *Analogue modeling of instabilities in crater lake hydrothermal systems*, J. Geophys. Res., 110, B02212, 2005

Experimental and numerical study of flows in a precessing triaxial ellipsoid

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Fluid layers are a common feature of celestial bodies, for example in the form of liquid iron cores or subsurface oceans. The forced orbital perturbations of the celestial body such as precession, libration or nutation will drive flows in these fluid layers leading to kinetic energy dissipation and in some cases self-generation of magnetic fields. While the dynamics in a spherical shell or spheroidal geometry have been investigated experimentally, theoretically and numerically, the case of an ellipsoidal planet has received less attention. We investigate in a coupled numerical and experimental study the flows driven by the precession of an ellipsoidal cavity.
The experimental setup consists of a rapidly rotating triaxial ellipsoidal container filled with water and mounted on a turntable that mimics the precession of the planet. Velocity measurements using classical ultrasonic Doppler velocimetry (UDV) are complemented by dynamic pressure recordings to infer symmetry properties of the flows in the container.
We aim to study the base flow in the precessing ellipsoid with a particular focus on the resonances between the Poincare mode in the system and the precessional forcing as predicted by Noir and Cébron (JFM, 2013) and Vidal (Thesis, 2018). In addition, we characterize the onset of the instabilities and compare our results with the analytical prediction of Vidal (Thesis, 2018). We use the experiment to explore the numerically inaccessible range of parameters at low Ekman numbers and larger precessional frequencies.

The role of coherent structures in hydromagnetic dynamos: a wavelet-based approach

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Turbulent dynamos are present in many astrophysical systems. We consider dynamo action in turbulent flows that contain coherent structures. In particular we aim to assess the extent to which the growth rate of such a dynamo is controlled by the larger scale coherent stuctures in the flow, as opposed to the the small-scale turbulent eddies. One approach to this problem is to apply Fourier filtering to the velocity field (Tobias & Cattaneo 2008) to identify the dominant scales of motion in the dynamo. However, localised coherent structures are not always well-represented by such filtering schemes, with information distributed across many Fourier components. An alternative approach is to use wavelets, which are better suited to describing such localised structures. We will present simulations of 2.5D dynamo action, using flows derived from the active scalar equations. The flows are filtered in wavelet space, retaining only those wavelet coefficients whose magnitude exceeds a certain threshold; only a small fraction of the relevant modes must be kept in order to ensure the retention of the dominant coherent structures. We will describe the extent to which the dynamo growth rate for these filtered flows depends upon the filtering threshold, comparing our findings with comparable Fourier-based filters. Based upon this comparison of these two filtering approaches, we will discuss the extent to which such wavelet-based methods could be used to increase the efficiency of numerical approaches to modelling turbulent astrophysical dynamos.

Characterizing Convection in the Solar Interior

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Turbulent convection is present in the outer 30 % of the Sun, where it is the dominant heat transport mechanism. Convection drives the solar dynamo, transports angular momentum, maintains meridional circulation, and excites both seismic acoustic and Rossby waves.

Solar convection is taking place in an extreme parameter regime compared to laboratory Rayleigh-Bénard convection. The Reynolds and Rayleigh numbers for solar convection are very high (Re $\sim 10^{14}$, Ra $\sim 10^{21} - 10^{24}$). The steep density stratification of the plasma results in highly depth-dependent conditions and difficulties in the numerical modeling.

The large-scale components of convection are neither well characterized observationally, nor well-reproduced by numerical models, especially at depth (Gizon and Birch, 2012). At the surface, simulations yield flow amplitudes that are at least an order of magnitude larger than observations.

Helioseismology can be used to measure flows in the solar interior by measuring Doppler shifts of seismic waves. An important aim of helioseismology is to well characterize convection in the Sun. Especially, we would like to determine the depth of narrow downdrafts that are predicted by theory, and to characterize the effect of rotation on convection.

In my presentation, I will give an introduction to the latest helioseismic methods for measuring flows in the solar interior (e.g., Böning et al., 2016; Böning, 2017) and I will show how they can be applied to solve some of the remaining questions about solar convection.

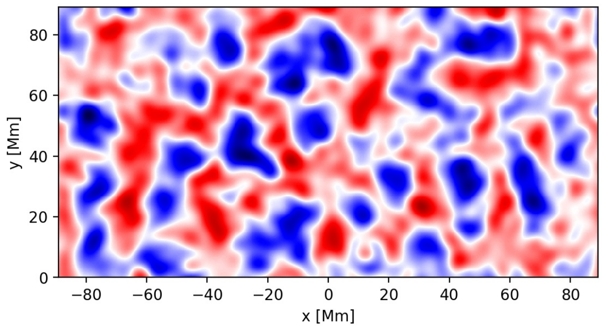

Figure 1: Map of the horizontal divergence of solar convective flows at scales of about 30 Mm at $1-2$ Mm below the surface. The colour scale spans values between $\pm 150 \times 10^{-6}\,\mathrm{s}^{-1}$. The divergence was measured with time-distance helioseismology, which is similar to seismic interferometry.

References

Böning, V. G. A.: 2017, *Ph.D. Thesis*, [ADS], [DOI]

Böning, V. G. A., Roth, M., Zima, W., Birch, A. C., and Gizon, L.: 2016, *The Astrophysical Journal* **824**, 49, [ADS], [DOI]

Gizon, L. and Birch, A. C.: 2012, *Proceedings of the National Academy of Science* **109**, 11896, [ADS], [DOI]

Comparative statistical analysis of zonal jet flows from laboratory and Global Climate Model.

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The strong zonal (i.e. east–west) jet flows on the gas giants, Jupiter and Saturn, have persisted for hundreds of years. Zonal jets are large-scale features ubiquitous in planetary atmosphere and result from multi-scales interactions in rapidly rotating turbulent flows. Here we use a new Saturn Global Climate Model (GCM) coupling seasonal radiative model tailored for Saturn with a new hydrodynamical solver, developed in *Laboratoire de Météorology Dynamique*, which uses an original icosahedral mapping of the planetary sphere to ensure excellent conservation and scalability properties in massively parallel computing resources. Strong and quasi-steady Saturn jets are reproduced in our GCM simulations with both unprecedented horizontal resolutions (reference at 1/2 ◦ latitude/longitude), integrated time (up to ten simulated Saturn years), and large vertical extent (from the troposphere to the stratosphere). We perform statistical analysis on the resulting flows to explore scales interactions and kinetic energy distribution at all scale. It appears that horizontal resolution as well as subgrid-scale (unresolved) dissipation, included as an additional hyperdiffusion term, strongly affect jets' intensity and statistical properties. In parallel, we set the first laboratory device capable to achieve the relevant regime to form planetary like zonal jets. We report that in a rapidly rotating cylindrical container, turbulent laboratory flow naturally generate multiple, alternating jets that share basic properties of the one observed on gas planets. By performing similar statistical analysis we directly confront flow properties of laboratory versus GCM generated jets and point out the effect of limited numerical resolution and subgrid-scale assumptions on atmospheric dynamics at large/jets scale.

A singular vorticity wave packet within a rapidly rotating vortex

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This study considers a free vorticity wave packet propagating within a rapidly rotating vortex in the quasi-steady régime, a long time after the wave packet strongly and unsteadily interacted with the vortex.We study singular, nonlinear, helical and asymmetric shear modes inside a linearly stable, columnar and axisymmetric vortex in the f-plane. The amplitude modulated mode enters resonance with the vortex at a certain radius r_c, where the phase angular speed is equal to the rotation frequency. The singularity in the modal equation at r_c strongly modifies the flow in the 3D helical critical layer, the region around r_c where the wave/vortex interaction occurs. This interaction generates a vertically sheared 3D mean flow, of higher amplitude than the wave packet, and strongly affecting the nonlinear wave dynamics. The chosen envelope régime assumes the formation of a mean radial velocity of the same order as the wave packet amplitude, leading to that the streamlines experience a spiral motion in the neighborhood of the critical layer. Radar images frequently show such spiral bands in tropical cyclones or tornadoes. Through matched asymptotic expansions, we find an analytical solution of the leading-order equations inside the critical layer. The generalized Batchelor integral condition applied to the quasi-steady 3D motion inside the separatrices yields a leading-order non-uniform 3D vorticity. The critical layer pattern, strongly deformed by the mean radial velocity, loses its symmetries with respect to the azimuthal and radial directions, which makes the leading-order mean radial wave fluxes non zero. Finally, a stronger wave/vortex interaction occurs with respect to the previous studies where a steady vortical neutral mode or a larger-extent envelope was involved.

Hypergravity wave turbulence

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Wave turbulence studies the statistical and dynamical properties of an ensemble of nonlinear waves undergoing resonant interactions. This phenomenon occurs in a large range of physical systems : internal waves or surface waves in oceanography, plasma waves in astrophysics, spin waves in solids, nonlinear waves in optics. The theory of wave turbulence developed in the 1960s, leads to analytical predictions on the wave energy spectrum, and has since been applied in almost all domains of physics involving waves. The expression of the spectrum is generally a power law, similarly to the phenomenological cascade of Kolmogorov in usual turbulence. In the case of surface waves, a transition was experimentally observed between gravity wave turbulence and capillary wave turbulence.

We report on the observation of gravity-capillary wave turbulence on the surface of a fluid in a high-gravity environment. By using a large-diameter centrifuge, the effective gravity acceleration is tuned up to 20 times the Earth gravity. The transition frequency between the gravity and capillary regimes is then increased up to one decade. The wave spectrum displays frequency power-laws in each regime that are found to be independent of the gravity level and of the wave steepness. The nonlinear and dissipation timescales are experimentally found to be independent of the gravity level and of the scale, contrarily to weak turbulence predictions. This comes from the important role of the large-scale container modes that authorizes a cumulative energy transfer through the scales in addition to the usual transfer by nonlinear wave interactions.

We thank European Space Agency (ESA) for the access to the LDC facility through the proposal CORA-GBF-2018. We thank M. Mélard for his technical help on the experimental setup. Part of this work was supported by the French National Research Agency (ANR DYSTURB project No. ANR-17-CE30-0004), and FNRS.

Multiscale Modeling of Strongly Stratified Turbulence

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Strongly stratified turbulence is a fundamental agency for diabatic mixing in numerous geophysical flows [1]. Nevertheless, parameterization of the mixing efficiency in stratified turbulence remains a subject of debate, particularly in physically-relevant parameter regimes in which the Reynolds number $Re \to \infty$ while the Froude number (an inverse measure of the stratification strength) $Fr \to 0$. In this extreme parameter regime, the flow is dominated by highly anisotropic structures with horizontal scales much larger than their vertical scales. Owing to their relative horizontal motion, these structures are susceptible to stratified shear (e.g. Kelvin–Helmholtz and Holmboe) instabilities that drive spectrally non-local energy transfers. Collectively, these attributes make both DNS and LES of stratified turbulence especially challenging.

To surmount these difficulties, we perform a multiple-scale asymptotic analysis [2] of the non-rotating Boussinesq equations in the dual limit $Fr \to 0$ and $Re \to \infty$. The resulting *generalized quasi-linear* (GQL) model [3] captures the essential physics of strongly stratified shear turbulence: the slowly-evolving mean fields are governed by the hydrostatic primitive equations augmented with the vertical divergence of Reynolds stresses and buoyancy fluxes arising from the isotropic and non-hydrostatic fluctuation dynamics. Crucially, the usual closure difficulties associated with Reynolds averaging are circumvented here by exploiting the scale separation that emerges as $Fr \to 0$.

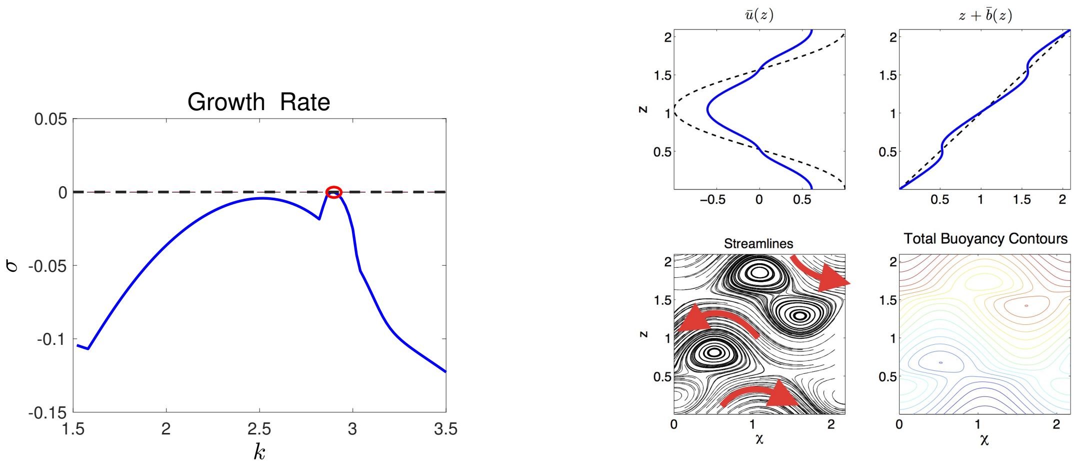

Figure 1: Exact coherent state (right) in strongly stratified Kolmogorov flow at $Fr = 0.01$ and $Re = 10^5$ supported by a single *marginally-stable* horizontal mode (left) with wavenumber $k = 2.9$.

The model is used to investigate the mixing efficiency of exact coherent states (ECS) arising in strongly stratified Kolmogorov flow (figure 1). The ECS are computed using a new methodology for numerically integrating slow–fast (G)QL systems [4] that obviates the need to explicitly resolve the fast dynamics of the stratified shear instabilities by exploiting a marginal-stability slaving principle.

[1] J.J. Riley & E. Lindborg (2012), *Recent Progress in Stratified Turbulence*, CUP, pp. 269–317.
[2] K. Julien & E. Knobloch (2007), *J. Math. Physics* **48**: 065405.
[3] B. Marston, G. Chini & S. Tobias (2016), *Phys. Rev. Letters* **116**: 214501.
[4] G. Michel & G. Chini (2019), *Proc. Roy. Soc. A* (in revision).

Variability of stochastically forced beta-plane zonal jets

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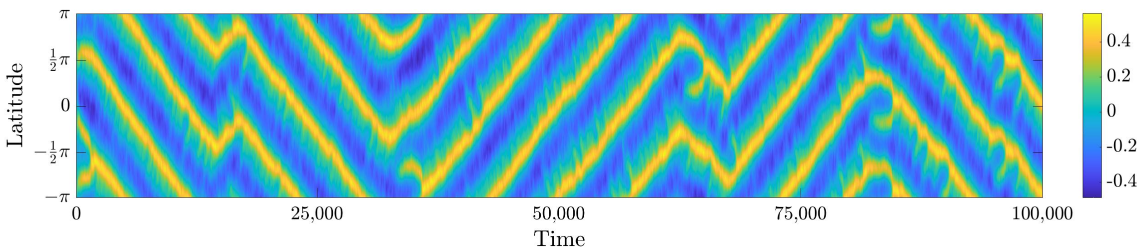
Zonal jets are strong and persistent east-west flows that arise spontaneously in planetary atmospheres and oceans. They are ubiquitous, with key examples including mid-latitude jets in the troposphere, multiple jets in the Antarctic Circumpolar Current and flows on gaseous giant planets such as Jupiter and Saturn. Turbulent flows on a beta-plane lead to the spontaneous formation and equilibration of persistent zonal jets. However, the equilibrated jets are not steady and the nature of the time variability in the equilibrated phase is of interest both because of its relevance to the behaviour of naturally occurring jet systems and for the insights it provides into the dynamical mechanisms operating in these systems.

Variability is studied within a barotropic beta-plane model, damped by linear friction, in which stochastic forcing generates a kind of turbulence that in more complicated systems would be generated by internal dynamical instabilities such as baroclinic instability. This nonlinear (NL) system is used to investigate the variability of zonal jets across a broad range of parameters. Comparisons are made with two reduced systems, both of which have received attention in recent years. A quasilinear (QL) model, in which eddy-eddy interactions are neglected, permitting only nonlocal interactions between eddies and the zonal mean flow, is studied in addition to a model employing direct statistical simulation (DSS) in which the flow statistics, truncated at second order in equal-time cumulants, are solved for directly. Each system reveals a rich variety of jet variability. In particular, the NL model is found to admit the formation of systematically migrating jets, a phenomenon that is observed to be robust in subsets of parameter space. Jets migrate north or south with equal probability, occasionally changing their direction of migration (see figure 1).

Figure 1: A latitude-time plot illustrating the zonal mean zonal velocity field from the NL model. A pair of jets equilibrate and systematically migrate either north or south, occasionally and spontaneously changing their direction of migration.



Surface current retroflection and vortices detachment under varying angle of a cape: Experimental results

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The quasi-periodic formation of coherent eddies during retroflection of an initially steady surface current is examined. As in prior experimental studies, retroflection was simulated for various conditions, corresponding to different combinations of cape angle and surface current speed. The simulations were conducted on a stratified domain under rotation. Results indicate eddy size and shape, detaching frequency, and coherence, depend on cape and the upstream speed. Eddies detach at a higher rate for 40 and 80 degree cape angles. Other configurations did not show either a regular eddy formation nor detaching. Eddy size was related to the internal Rossby radius of deformation (Rd) as predicted by theory. Current displacement towards the rotation axis in our experiments prior to eddy detachment was from 3.1 to 3.5 Rd . Retroflection angle was proportional to detachment period T for each cape angle: $6T$ for 80 degrees, and $3T$ for 40 degrees. We conclude that displacement toward the center of the tank is a β-effect consequence and eddy detachment is a result of eddy momentum increase from the incident current due to advection. Similarity was analyzed with retroflection present in two oceanic flows: Cabo Corrientes eddies. Eddy vorticity profile, dimensionless quantities related to moving speed, retroflection distance, eddy size, and vorticity for both oceanic flows are in agreement with our results.

Rossby modes in stellar polytropes

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Helioseismic inversions have recently characterised a new component of the solar oscillation spectrum: large-scale vorticity waves with retrograde phase velocity in the shallow subsurface layers of the Sun. Those waves are believed to be sectoral Rossby waves, or r-modes, owing to their characteristic dispersion relation. The fine understanding of these modes, and in particular their behaviour in neutrally stable layers remains elusive. Here, we use a perturbation method for the determination of non axisymetric r-modes of a slowly and uniformly rotating polytrope of arbitrary index n. We solve an eigenvalue problem with zero-boundary conditions to determine the frequency and displacement field to the fourth and second order, respectively, in the angular velocity. This allows us to investigate the properties of the modes and their frequencies as $n \to \frac{3}{2}$, and $A \to 0$, A being the Ledoux function characterising stratification 1.

We also investigate the effect of asphericity of the equipotential surfaces on the mode frequencies and eigenfunctions. We discuss the properties of the sectoral modes of first radial order, which behave as f-mode, independently of the value of A, and show that their radial dependence in the spheroid scales as x^m, m being the azimuthal wavenumber, and x the average radius of the equipotential level. Our results are a first step in understanding the Rossby waves observed in the Sun, but further developments are required to get a realistic picture, notably the inclusion of the effects of differential rotation, both in radius and latitude.

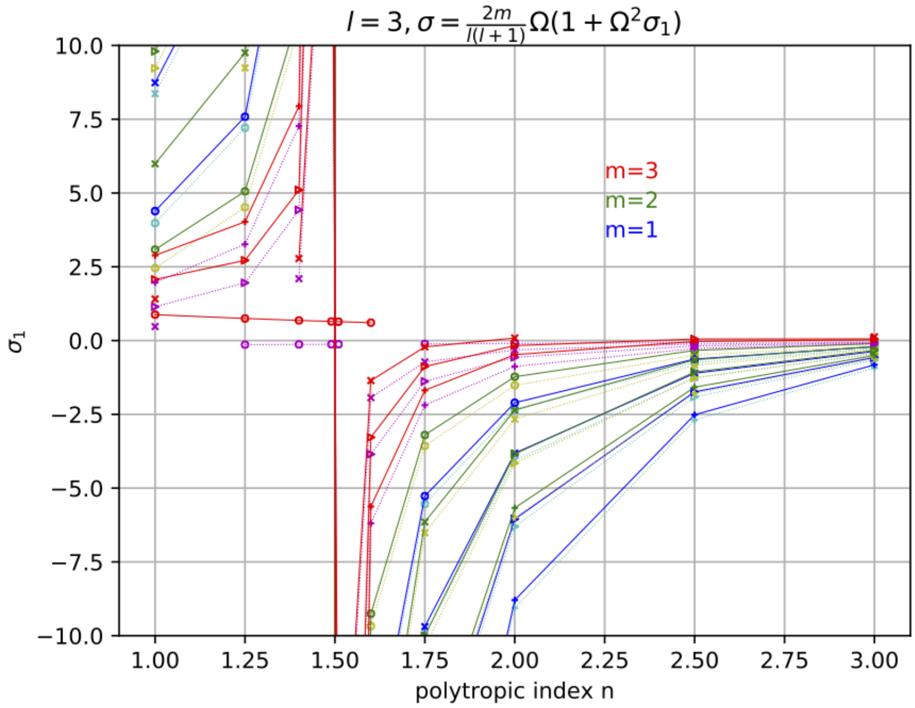

Figure 1: Eigenvalues as a function of polytropic index, for $l = 3$ and $m = 1, 2, 3$ (colour coded as indicated on the figure) and different values of the radial order k : circles, $k = 1$, crosses $k = 2$, triangles $k = 3$, pluses$k = 4$, for the second order term of the frequency expansion. The spherically symmetric solutions are given in dotted lines (and a slightly different hue for corresponding m values), and the solid lines show the frequencies as a function of n including the influence of the distortion of a rotating star.

Toward magnetostrophic dynamos

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Dynamo action in a rotating spherical domain is thought to account for the magnetic field of planets and stars. Whereas the equations governing this mechanism are well established, the parameter regime relevant to natural dynamos is out of reach of current numerical resources. I will discuss how the relevant forces balance can be approached in numerical models. Numerical models of the geodynamo are usually classified into two categories: dipolar modes, observed when the inertial term is small enough; and multipolar fluctuating dynamos, for stronger forcing. In addition to these two branches, widely discussed in the literature, a third regime has been identified by Dormy (2016), who pointed toward a distinguished limit (or path in the parameters space). This mode corresponds to a strong-dipolar branch which appears to approach, in a numerically affordable regime, the magnetostrophic limit relevant to the dynamics of the Earth's core. I will discuss the transitions between these states and point to the relevance of this strong dipolar state to Geodynamo modelling.

References:

Emmanuel Dormy, Ludivine Oruba and Ludovic Petitdemange
Three branches of dynamo action,
Fluid Dyn. Res., **50**, 1 (2018).

Emmanuel Dormy
Strong-field spherical dynamos
J. Fluid Mech., **789**, 500-513 (2016).

Interactions between tidal flows and convection

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Tidal interactions are important in driving spin and orbital evolution in various astrophysical systems such as hot Jupiters, close binary stars and planetary satellites. The fluid dynamical mechanisms responsible for tidal dissipation in giant planets and stars remain poorly understood. One key mechanism is the interaction between tidal flows and turbulent convection. This is thought to act as an eddy viscosity in damping large-scale tidal flows, but there exists a long-standing controversy over the efficiency of this mechanism in the limit of large tidal frequencies (which is the relevant regime in many astrophysical applications).

We explore the interaction between tidal flows and convection as a mechanism for tidal dissipation using hydrodynamical simulations. Our approach is to study the interaction between an oscillatory background shear flow, which represents a large-scale tidal flow, and the convecting fluid inside a small patch of a star or planet. We simulate Rayleigh-Bénard convection in this Cartesian model and explore how the effective viscosity of the turbulence depends on the tidal (shear) frequency.

We will present the results from our simulations to determine the effective viscosity, and its dependence on the tidal frequency in both laminar and weakly turbulent regimes. We will also present our extension to the theoretical framework of Ogilvie and Lesur (2012), so that it applies to Rayleigh-Bénard convection, which we will use to interpret and explain some of our results. We will focus on the scaling of the effective viscosity with tidal frequency in the limit of large tidal frequencies. We will also demonstrate, using both analytical theory and numerical simulations, that negative effective viscosities are possible in this system (corroborating a tentative finding in Ogilvie & Lesur, 2012). The astrophysical implications of our results will be briefly discussed.

Sample LaTeX abstract for talks and/or posters

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I present an introduction to the dynamo effect, i.e. the generation of a magnetic field by the motion of an electrically conducting flow and emphasize the effect of the turbulent nature of the flow that is involved in most realistic situations both in laboratory experiments and in planetary or stellar dynamos. Turbulence can strongly affect the dynamo threshold as well as the geometry of the magnetic field that is generated by the dynamo process. It also affects qualitatively the scaling law for the magnetic energy generated above threshold. In contrast, secondary instabilities such as the one responsible for periodic or random reversals of the magnetic field, can be understood using low dimensional dynamical systems that describe the interaction of a few modes. Turbulent fluctuations only provide the amount of noise required to trigger the transitions between metastable states. The lectures are organized as follows:

- The dynamo effect: an energy transformation mediated by an instability process
- The approximation of magnetohydrodynamics
- The energy budget and some necessary conditions for dynamo action. Anti-dynamo theorems
- Examples of laminar dynamos
- The problem of turbulent dynamos
- Fast versus slow dynamos. Small versus large scale dynamos
- Scale separation. Mean field magnetohydrodynamics
- Nonlinear saturation of the magnetic energy above the dynamo threshold
- Effect of turbulence on the dynamics of the magnetic field above threshold
- Models for field reversals

Extreme events in stratified turbulence

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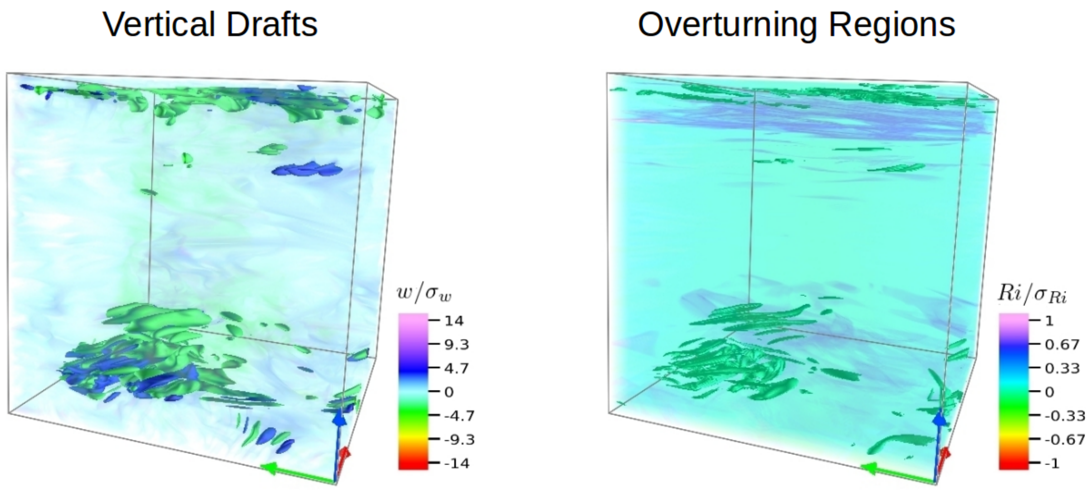
We investigate the large-scale intermittency of vertical velocity and temperature, and the mixing properties of stably stratified turbulent flows using both Lagrangian and Eulerian fields from direct numerical simulations of the Boussinesq equations with periodic boundary conditions, in a parameter space relevant for the atmosphere and the oceans. Over a range of Froude numbers of geophysical interest ($\approx 0.05-0.3$) we observe very large fluctuations of the vertical components of the velocity and the potential temperature, localized in space and time, with a sharp transition leading to non-Gaussian wings of the probability distribution functions. This behavior is captured by a simple model representing the competition between gravity waves on a fast time-scale and nonlinear steepening on a slower time-scale. The existence of a resonant regime characterized by enhanced large-scale intermittency, as understood within the framework of the proposed model, is then linked to the emergence of structures in the velocity and potential temperature fields, localized overturning and mixing (see figure). Finally, in the same regime we observe a linear scaling of the mixing efficiency with the Froude number and an increase of its value of roughly one order of magnitude. (*Feraco et al.; Europhysics Letters; 123, 2018, 44002*)



Left: Rendering of the vertical velocity w normalized by the variance (σ_w) in a stratified flow. A threshold is used to highlight the presence of intense vertical drafts ($> 3\sigma_w$) which appear as large-scale structures. Right: Rendering of the pointwise gradient Richardson number ($Ri = N(N - \partial_z\theta)/(\partial_z v_\perp)^2$) normalized by the variance (σ_{Ri}) for the same flow. Regions prone to develop overturning, with $Ri/\sigma_{Ri} < 0.004$, are visualized using opaque colors.

Wave and vortex generation at baroclinic unstable fronts

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Density fronts separate cold from warm fluid or air masses and therewith play an important role for the energy distribution in the Earth oceans and planetary atmospheres. The high and low pressure regions that emerge from their instability govern our daily weather, whereas their global long-term evolution is relevant for climate. Density fronts maybe generated by imposing a horizontal shear on a fluid with a stable density gradient, such as due to the spin-up in differentially rotating fluids or, in flows that are subjected to a lateral temperature gradient by means of the thermal wind balance.
In the laboratory, we consider a differentially rotating two-layer fluid, and focus on the baroclinic unstable regime with amplitude vacillation which is characterised by a periodic saturation of the baroclinic wave amplitude and formation of intense vortices, and subsequent relaxation to quasi-stable state. The vortex formation is found to be preceded in certain cases by the presence of small-scale waves.
Using a new spatiotemporal analyses of high-resolution images of the flow evolution from dye observations and Fourier analyses, we are able to capture the evolution of the small-scale waves, the interaction between small-waves with the baroclinic life-cycle, in addition to the formation of the vortices observed from PIV measurements. We show, by exclusion of other types of waves, that the waves occurring at the front are spontaneously emitted, and that their accumulation precedes the formation of vortices for low Rossby numbers. Exceeding a certain threshold, large-scale waves dominate and the emerging vortex structure is barotropic. Possible mechanisms will be discussed.

In addition, the baroclinic unstable regime in a linearly stratified fluid is shortly discussed in the context of former results on spin-up from rest. For tank aspect-ratio's close to 1, the baroclinic instability of the front between the stratified interior and the weakly stratified exterior leads to an unstable core region of which the mode corresponds to the expected baroclinic unstable mode. For small aspect-ratio's (flat tanks) the general features of two-layer instabilities are recovered.

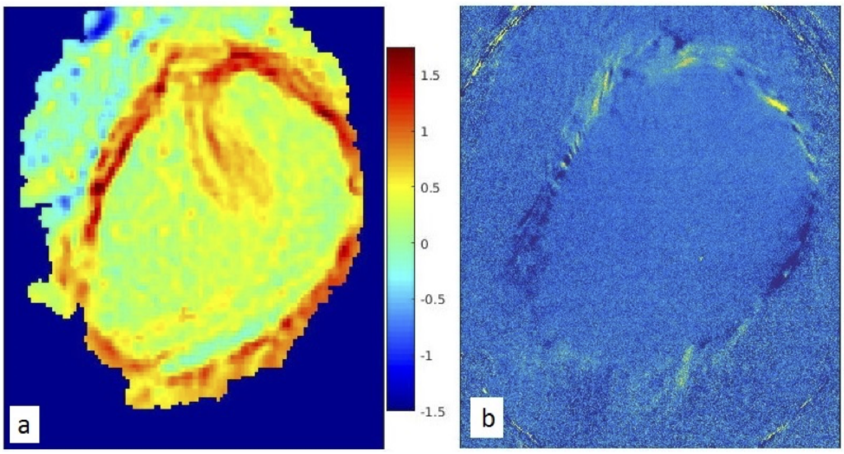

Figure 1: Vorticity field (a) and the vortex emerging from the front marked by the red vorticity contour, and (b) corresponding density field (filtered) with small-scale wave activity.

The scientific elucidation of the ship-holder myth at Actium

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The battle of Actium was pivotal in the advent of the Roman Empire with the victory of Octavian against Antony and Cleopatra. Since twenty centuries, the scholars have tried to understand the reasons of the Antonians defeat. Indeed, the Antonian fleet with huge boats should have won against the smaller Octavian's ships. A legend was invoked by the admiral Pliny the Elder to explain the outcomes of the battle: Neptune had favored Octavian via the fish echeneis-remora, the ship-holder. Here, based on our oceanographic data, we compute the ship resistance of representative galleys of both armadas, and recreate battle's conditions in a towing tank. We show different wake patterns, and suggest that the resistance encountered by the Antonian galleys had a visual signature, set by the ship draft to depth ratio. This particular wake pattern has triggered the myth in the ancient times. Our interdisciplinary approach, using modern methods and techniques, shed new light in an obscure point of Ancient History, and presents a whole new scientific approach to History.

Turbulence of gravitational waves in the primordial universe

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Wave turbulence is a paradigm for studying turbulent systems composed of weakly non-linear waves. In this presentation I will first introduce the theory of wave turbulence and discuss the possibility of deriving exact solutions. This part will be illustrated by several experiments and direct numerical simulations coming from different domains (hydrodynamics, astrophysical plasmas). Then, I will present a new application relevant to cosmology and the primordial universe: gravitational wave (GW) turbulence. A general introduction to cosmology will be made where in particular I will present the Einstein's equations of general relativity and the properties of GW. I will show that the non-linear nature of the Einstein's equations allows us to develop a wave turbulence theory (1) which is close to elastic wave turbulence. This theory is built from a diagonal space-time metric reduced to the variables t, x and y (2). It is characterized by a dual cascade driven by 4-wave interactions with a direct cascade of energy and an inverse cascade of wave action. In the latter case, the isotropic Kolmogorov-Zakharov spectrum has the power law index $n = -2/3$ involving an explosive phenomenon. I will illustrate this explosive cascade with a nonlinear diffusion model that retains only strongly local interactions (3). I will show that an anomalous spectrum (with $n > -2/3$) emerges which is understood as a self-similar solution of the second kind. Finally, I will present a plausible scenario for the cosmological inflation based on the inverse cascade and the formation of a condensate (4).

(1) Galtier & Nazarenko, Turbulence of weak gravitational waves in the early universe, Phys. Rev. Lett. **119**, 221101 (2017).
(2) Hadad & Zakharov, Transparency of strong gravitational waves, J. Geom. Phys. **80**, 37 (2014).
(3) Galtier, Nazarenko, Buchlin & Thalabard, Nonlinear diffusion models for gravitational wave turbulence Physica D **390**, 84 (2019).
(4) Galtier, Nazarenko & Laurie, Cosmic inflation driven by space-time turbulence (2019).

Angular momentum of magnetohydrodynamic modes in a rotating triaxial ellipsoid

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Nowadays, the main Earth's magnetic field is accurately monitored from satellites placed on a low orbit. Together with records of the Earth's rate of rotation, the magnetic field observations give precious information about magnetohydrodynamic (MHD) waves in the Earth's fluid core. The propagation of these waves is sensitive to the properties of the core-mantle boundary: height of the interface with respect to a mean sphere; symmetry about the rotation axis; electrical conductivity of the solid mantle adjacent to the fluid core. We develop a 2-D reduced model of the fluid dynamics from a Lagrangian formulation to account for the non-spherical core-mantle boundary. The simplification of such a quasi-geostrophic model rests on the invariance of the fluid velocity parallel to the rotation axis. Additionally, in the ellipsoidal case the velocity components can be expressed as polynomials of the Cartesian coordinates. These approaches enable us to calculate MHD modes both analytically and numerically. We investigate and quantify the angular momentum of these modes, in particular the torsional modes, and check if they can exert a torque on the mantle.

DAMPING OF BALANCED MOTIONS DURING CRITICAL REFLECTION OF INERTIAL WAVES OFF THE SEA SURFACE AT OCEAN FRONTS

NICOLAS GRISOUARD, LEIF N. THOMAS

At oceanic fronts, due to the sloping isopycnals and associated thermal wind shear, the possible directions of the group velocity of inertia-gravity waves (IGWs) depart from the classical St Andrew's cross. However, waves oscillating at the Coriolis frequency, f, keep one of these directions horizontal, while the other direction allows for vertical propagation of energy. This implies the existence of critical reflections of inertial waves off the sea surface, after which incident wave energy cannot escape. This is analogous to the classical critical reflection of IGWs in a quiescent medium off a sloping bottom. We present a series of numerical experiments exploring parameter space that highlight properties of critical ($\omega = f$), sub-critical ($\omega > f$), and super-critical ($\omega < f$) reflections. Super-critical reflections are favorable to triadic resonant interactions and therefore exhibit significant propagation of super-harmonic energy back downwards, while sub-critical reflections inhibit triadic interactions and dissipate energy locally. We also report on irreversible energy exchanges between IGWs and geostrophically-balanced frontal flows that are enabled by friction and the modification of IGW-physics at fronts. This is exacerbated during critical reflections where intense frictional effects under the surface induce a net transfer of energy from the balanced flow to ageostrophic motions, which are subsequently dissipated.

Impacts of inertial/symmetric instabilities on ocean fronts

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Oceanic submesoscale density fronts are structures in geostrophic and hydrostatic balance. They tend to be small (100 m to 10 km wide at mid-latitudes) and ubiquitous features of the near0surface of the oceans. They are also prone to various instabilities, which oceanographers believe may be key to understanding the kinetic energy budget of the ocean, as well as their effects on gas and nutrients exchanges between the surface and the abyss.

In this presentation, we focus on a particular type of frontal instability, namely inertial and/or symmetric instabilities. We present a series of two– and three–dimensional numerical experiments to investigate energetic impacts of these instabilities on fronts. We first argue that contrary to parameterization prototypes that are currently being developed, drainage of available potential energy from the geostrophic flow can be a leading-order source of their growth. We also argue that a front is relatively robust when experiencing these instabilities. We also illustrate how one of the unexpected by-product of these instabilities is a strong radiation of internal waves, which we interpret as a near-resonance between the fastest growing modes of the instability and the polarization relations of internal waves.

Our set of experiments covers the submesoscale portion of a three-dimensional parameter space consisting of the Richardson and Rossby numbers, and a measure of stratification or latitude. Parameters that are difficult to control relate to choices regarding the dissipation operator, and we caution modellers about a possibly large impact of such choices on the simulated dynamics of the instability.

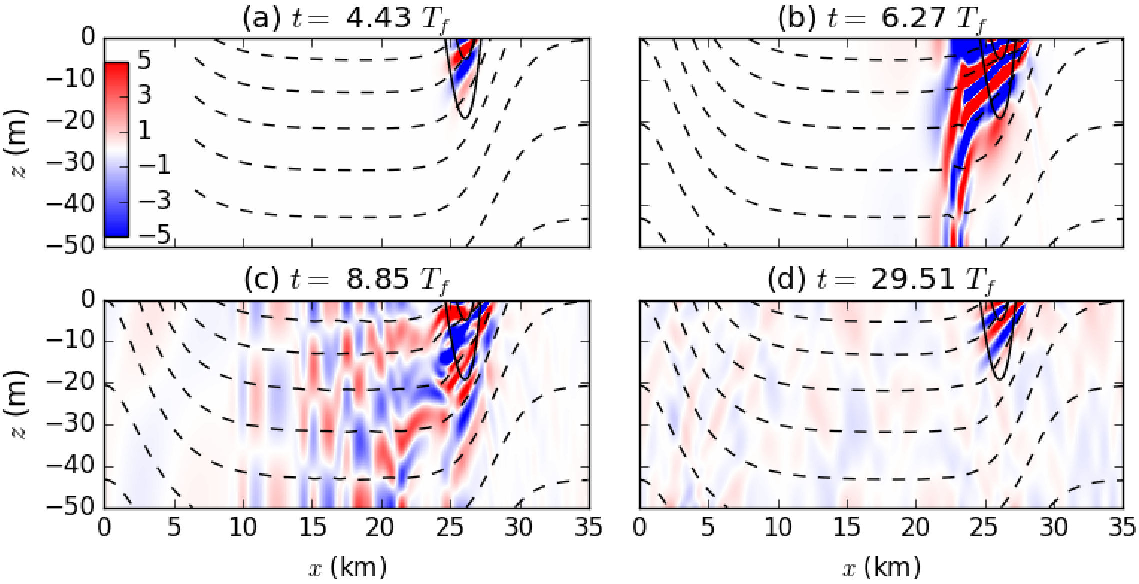

Figure 1: Evolution of an inertial/symmetric instability. Coloured shades: in-plane horizontal velocity (mm s^{-1}); solid lines: initial iso-potential vorticity contours; dashed lines: initial isopycnal contours.

Turbulent convective lengthscale in planetary cores

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Convection in planetary cores is thought to be turbulent and constrained by rotation. Key properties of convection, such as the characteristic flow velocity and lengthscale, are poorly quantified in planetary cores due to their strong dependence on planetary rotation, buoyancy driving and magnetic fields, which are all difficult to model under realistic conditions. In this work, we explore rapidly-rotating turbulent convection in the absence of magnetic fields with a combination of numerical spherical models in 3D (down to Ekman number $Ek = 10^{-8}$ and up to Reynolds numbers $Re = 6000$) and in 2D (down to $Ek = 10^{-11}$ and up to $Re = 70000$). We find that that the characteristic convective lengthscale, $\mathcal{L}_t$, becomes independent of the viscosity and is entirely determined by the flow velocity and planetary rotation for Ekman numbers $Ek \leq 10^{-8}$. The steepness of the kinetic energy spectrum for scales smaller than $\mathcal{L}_t$ implies that $\mathcal{L}_t$ is essentially a lower limit for the energy-carrying lengthscales. For the first time, we are able to model realistically convection in small non-magnetic cores such as the Moon (where $Ek \approx 10^{-11}$). Although larger planetary core conditions remain presently out of reach, the independence of the results on the viscosity allows a straightforward extrapolation to these objects. For Earth's core conditions, we find that the turbulent convective scale in the absence of magnetic fields would be approximately 30 km, which is orders of magnitude larger than the 10-m viscous lengthscale.

Stationary Taylor state magnetic fields and Magneto-Coriolis waves

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The geodynamo is driven by the motion of fluid within the Earth's outer core. In this motion, which is governed by the MHD equations, rotational forces are dominant over inertial and viscous forces, which means the Ekman and Rossby numbers are very small. Hence we follow the approach proposed by Taylor in 1963, of an inertia-free and viscous-free model as the asymptotic limit of Earths dynamo. In this theoretical limit of a magnetostrophic balance, a certain necessary condition, now well known as Taylor's constraint, must hold. We construct the first magnetic fields that exactly satisfy this constraint and are steady (stationary Taylor states). These states are distinct from previous simple examples studied because they drive an associated non-zero velocity. Not only do these serve as simple prototype models for rotationally dominant quasi-steady planetary magnetic fields, but they define a dynamically self consistent background state about which we can investigate Magneto-Coriolis wave perturbations. Because these waves evolve on the same timescale as the magnetic field, they must also satisfy Taylor's constraint. We study these waves using a fully three-dimensional model and discuss how the presence of the non-quiescent background flow impacts upon their behaviour.

Determining the simplest and most efficient axisymmetric kinematic dynamos in a sphere

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The Earth's magnetic field is generated by the motion of conductive fluid in its outer core. There are various ways to study the details of this mechanism. While direct numerical simulations can reproduce a number planetary magnetic fields features, these simulations cannot currently access the parameter regime relevant to planetary dynamos, and often produce flows which are too complicated to be physically interpreted. In an attempt to better characterise what kind of flow structures produce particular magnetic field features, we consider a simplified approach to the problem, the kinematic dynamo approximation. Here, a time-invariant fluid flow is prescribed and the resulting magnetic field is considered, neglecting the back-reaction of the magnetic field on the fluid flow. Dynamo action is achieved if the fluid flow is capable of sustaining a growing magnetic field against dissipation. The parameter which controls the strength of inductive to diffusive effects is the magnetic Reynolds number, Rm. The onset of dynamo action occurs at the critical magnetic Reynolds number, Rm_c. The aim of our study is to find the simplest and most efficient axisymmetric flows which act as kinematic dynamos in a sphere. These flows may be able to shed light on the essential physical processes which are necessary to generate dynamo action. We present optimised versions of three axisymmetric kinematic dynamos first proposed by Dudley and James (Proc. R. Soc. Lond. A, 425:407-429, 1989). These flows, which contain only one toroidal and one poloidal mode, are some of the simplest known functioning dynamos. Using a Lagrangian optimisation technique for steady flows in a sphere developed by Chen et al. (J. Fluid Mech, 839: 1-32, 2018), we found the smallest critical magnetic Reynolds number for each flow type when Rm is measured using an enstrophy-based norm. A Galerkin method was used, in which the spectral coefficients of the fluid flow and magnetic field expansions were updated in order to maximise the final magnetic energy after two diffusion times. The optimised flows display Rm_c that are up to four times smaller than the original Dudley-James flows. All Rm_c are quite similar, suggesting that there is only a weak preference for a flow dominated by particular modes. Two of the three flows display good alignment of the velocity and vorticity in the inner region of the sphere, resulting in significant helicity, known to enhance dynamo action. Furthermore, since we are seeking kinematic dynamos with the simplest possible flow structure, we consider the optimisation of single mode flows. Purely toroidal flows are known not to be able to sustain dynamo action, and no example of a purely poloidal single mode dynamo has been found to date. Using the Lagrangian optimisation algorithm, we present a strategy to search for the purely poloidal s_1^0 and s_2^0 kinematic dynamos. These would be the simplest kinematic dynamos found to date.

Rotating MHD waves and their implications for planetary dynamos

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The magnetohydrodynamics of rotating fluids–referred to as rotating MHD–describes situations where rotation occurs together with a magnetic field. Its relevance is found in geophysics and astrophysics including Earth's liquid iron core and Jupiter's metallic hydrogen region, in which the dynamo action is believed to operate. In the magnetostrophic dynamos, in which the Coriolis, pressure, and Lorentz forces dominate the force balance, unique wave motions can occur in both axisymmetric and non-axisymmetric modes. Identifying those wave motion could allow us to get insights about the planetary dynamos that are seated in the deep interiors. To explore the relevance of waves and the dynamics, we use direct numerical simulations of MHD dynamos driven by convection in rapidly rotating spherical shells.

Axisymmetric, torsional Alfvén waves are a special class of the MHD waves, as confined to cylindrical surfaces about the rotational axis. The excitation of the 4-6 year fluctuations in Earth's core and its link to the length-of-day variations have been shown. The state-of-the-art geodynamo simulations with the incompressible, Boussinesq approximation being assumed have supported the wave excitement and illustrated their propagation outwards, initiated at the bottom of the fluid core and damped at the top boundary to the rocky mantle. The speed can be a proxy for the strength of the radial magnetic field.

Magnetic Rossby waves are non-axisymmetric and typically travel in azimuth along the internal toroidal field. The presence of magnetic field splits the fundamental rotating wave into fast and slow modes: the slow one was proposed to account for the geomagnetic westward drift of a few hundreds of years. The long-hypothesized wave motion was recently exemplified in geodynamo models to reveal its propagation, riding on background zonal flows, and steepened waveforms, arising from nonlinear Lorentz terms. The detection however necessitates an update of historical geomagnetic data sets and/or its inverted core flow models. This will be the key to infer the hidden, toroidal field and to constrain the dynamo mechanism.

Exploration is extending to other planets, such as Jupiter. The gas giant's strong magnetic field and rapid rotation may reasonably host rotating MHD waves excited in the metallic region; compressibility of the fluid will bring some modifications. The ongoing Juno measurements have been defining the spatial and temporal structure of the intrinsic, magnetic field.

Adopting Jovian dynamo models coupling with the overlying molecular hydrogen region partly, we find Jovian torsional waves to be reflected at the metallic transition and to be standing, rather than travelling. Those wave properties may highlight the top of the metallic region, which has been poorly constrained. The zonal oscillations on timescales of ten years, at shortest, yield potential changes of the planet's length-of-day of amplitude no greater than tens milliseconds. Also, the deep-origin disturbances can trigger consequent variations of surface zonal wind at the molecular envelope. Nonaxisymmetric motion predominantly comprises of fast magnetic Rossby waves that travel eastwardly with speeds slightly faster than the nonmagnetic mode, with respect to the mean zonal flows. The correction terms, though they arise at the following order, could be used to evaluate the density variation and/or the magnetic field within the dynamo region.

Internal gravity waves, shear, and mixing in forced stratified turbulence

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The primary sources of energy in the ocean generate motions on very large scales, yet the closure of the global ocean energy budget requires dissipation by viscosity at millimetre scales. One pathway for the transfer of energy to these small scales is by the generation of turbulence directly from the large scale forcing. For example, strong surface winds directly force small-scale turbulence in the upper ocean which leads to a mixed layer of approximately uniform density, and tides pull water over rough topography resulting in localised turbulent mixing in specific regions.

Energy that is not dissipated close to these boundaries typically propagates away into the interior of the ocean as internal gravity waves. Far from the boundaries, the distribution of internal gravity waves is well described by the empirical Garrett–Munk spectrum [1]. Energy is thought to cascade along this spectrum from large scales to small scales via weakly nonlinear wave-wave interactions, until the spectrum cuts off at a scale of approximately 10m. At yet smaller scales, strongly nonlinear wave-wave interactions, shear instabilities and wave breaking lead to turbulent mixing, albeit through turbulence that is strongly affected by stratification.

This irreversible mixing is vital for maintaining the abyssal stratification of the ocean, and it also determines the rate of nutrient upwelling through the pycnocline, which controls the level of biological activity in the upper ocean. However this turbulent mixing is intermittent in both space and time, and the nature of the mixing is not well known. In regions such as the pycnocline, where the dynamics are well described by the internal wave spectrum, it is not clear whether shear-driven mixing or more efficient convective mixing is more prevalent.

To determine the importance of internal waves for modifying the nature of mixing in stratified turbulence, we perform direct numerical simulations of a Boussinesq fluid subject to three different types of large-scale body forcing. The first involves forcing randomly phased vortical modes, as applied by previous studies of stratified turbulence (e.g. [2]). The remaining simulations are forced by a field of internal gravity waves - one with the waves randomly phased at each time step, and the other with the forced waves propagating according to the dispersion relation. All simulations are initialised using a base state representative of the Garrett–Munk spectrum, with vertical shear accounting for waves on larger horizontal scales than the domain.

We identify how key quantities such as mixing efficiency and vertical diffusivity vary with the type of forcing, and isolate the mechanisms responsible for the differences. Since the background vertical shear varies with depth, we can also inspect the vertical structure of the flow to identify how the forcing interacts with the shear and how this leads to intermittent regions of increased dissipation. We investigate how well existing parametrisations of mixing based on fine-scale measurements capture this intermittency, and how they compare across the simulations with different forcing regimes. Finally, we look at the issue of sampling when measuring turbulent flows. We determine how much information about mixing can be accurately obtained from individual vertical profiles of velocity and density perturbations. From this sampling, we aim to improve the identification of shear driven mixing versus convective mixing in observational profiles.

References

[1] C. Garrett and W. Munk. Internal waves in the ocean. *Annual Review of Fluid Mechanics*, 11:339–369, 1979.

[2] A. Maffioli. Vertical spectra of stratified turbulence at large horizontal scales. *Physical Review Fluids*, 2:104802, 2017.

Dynamics of a reactive spherical particle falling in a linearly stratified layer

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Rocky planets such as Earth, Mercury or Ganymede have a liquid iron core which may be totally or partly stably stratified [1, 2]. The sedimentation of iron particles crystallizing due to the secular cooling of the planet [3] or the precipitation of oxides [4] implies complex dynamic features involving a turbulent wake, the generation of internal waves or collective behaviour of the solid crystals, etc. It also involves reactive solid particles which may crystallize/melt.

Beyond the geophysical application, this problem is, therefore, related to several current problems in fluid dynamics, which we address with the help of a laboratory-scale experiment. The behaviour of a particle falling in a stratified layer has already been studied for different regimes of small Reynolds or Froude numbers [5, 6]. However, the influence of a reactive particle on a stratified medium has been unexplored, especially for regimes of interest for geophysical applications (large Reynolds and Froude numbers). In a stratified environment, the fall velocity is reduced due to the higher drag coefficient. During its fall, a particle drags a less dense liquid mixed with the product of the melting/dissolution. Then, the drag coefficient depends on the mixing in the wake, and on the melting/dissolution rate.

I am conducting experiments in a large water tank with salinity stratification where an icy, salty sphere is released from the top. I use two cameras and particle image velocimetry (PIV) to track the fall of the particle and the dynamics of the surrounding environment. I examine the velocity and the rate of dissolution of the spherical particle in comparison to a theoretical model. I also characterize the influence on its surrounding environment - generation of internal waves, the quantity of energy dissipated, and the mixing of the stratified layer. All these quantities are non-linearly coupled, leading to complex and interesting dynamics.

References

[1] Gomi, H., Ohta, K., Hirose, K., Labrosse, S., Caracas, R., Verstraete, M. J., Hernlund, J. W., The high conductivity of iron and thermal evolution of the Earth's core, *Physics of the Earth and Planetary Interiors*, **224** (1), 88-103, (2013).

[2] Rückriemen, T., Breuer, D., Spohn, T., The Fe snow regime in Ganymede's core: A deep-seated dynamo below a stable snow zone, *Journal of Geophysical Research*, **120**, 1095–1118, (2015).

[3] Hauck, S. A., Aurnou, J. M., Dombard, A. J., Sulfur's impact on core evolution and magnetic field generation on Ganymede, *Journal of Geophysical Research*, **111**, (E9), 2156-2202, (2006).

[4] Badro, J., Siebert, J., Nimmo, F., An early geodynamo driven by exsolution of mantle components from Earth's core, *Nature*, **536**, (7616), 326-328, (2016).

[5] Mehaddi, R., Candelier, F., Mehlig, B. Inertial drag on a sphere settling in a stratified fluid, *Journal of Fluid Mechanics*, **855**, 1074-1087, (2016).

[6] Yick, K. Yeung, Torres, C. R., Peacock, T., Stocker, R., Enhanced drag of a sphere settling in a stratified fluid at small Reynolds numbers, *Journal of Fluid Mechanics*, **632**, 46-68, (2009).

Characterization of intermittency in the upper ocean

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Intermittency is a key property of turbulent flows such as the ocean. In this study, we investigate it in the upper ocean ($z \leq -500$ m) from in situ measurements of velocities provided by the Oleander project. The dataset consists on weekly profiles of horizontal velocities between New Jersey and Bermuda in the North Atlantic obtained by an ADCP mounted on a ship-of-opportunity. Rather than using the canonical approach of computing the velocity structure functions and, then, characterize the anomalous scaling, we computed the singularity exponents $h(\vec{x})$ of the gradient of longitudinal and traverse velocity components and the associated singularity spectra $D(h)$.

The preliminary analysis has been focused on the symmetry about the mode of the $D(h)$; the value of the most singular exponent h_∞, here approximated by $h_\infty \approx \min(h)$; and the amplitude of $D(h)$, here defined as $\Delta h^- \equiv h_d - h_\infty$, where h_d is the mode. The histograms of these three quantities can be found in the first row of the figure. Results unveils that the $D(h)$ are asymmetric about the mode, which is incompatible with symmetric models such as the Log-Normal model. Besides, Δh^- provides a quantification of the anomalous scaling of the structure functions as it can be seen by applying the Legendre transform to the $D(h)$ and h_∞ can be interpreted in oceanographic terms as the intensity of the strongest front. The comparison of these two quantities (second row of the figure) reveal a linear relationship between the intensity of fronts given by $\min(h)$ and the anomalous scaling given by Δh^-. Furthermore, the slope between these two quantities, which can be related to the intermittency parameter, shows a clear dependence with depth. Finally, our preliminary analysis also show that observations are compatible with the Log-Poisson model.

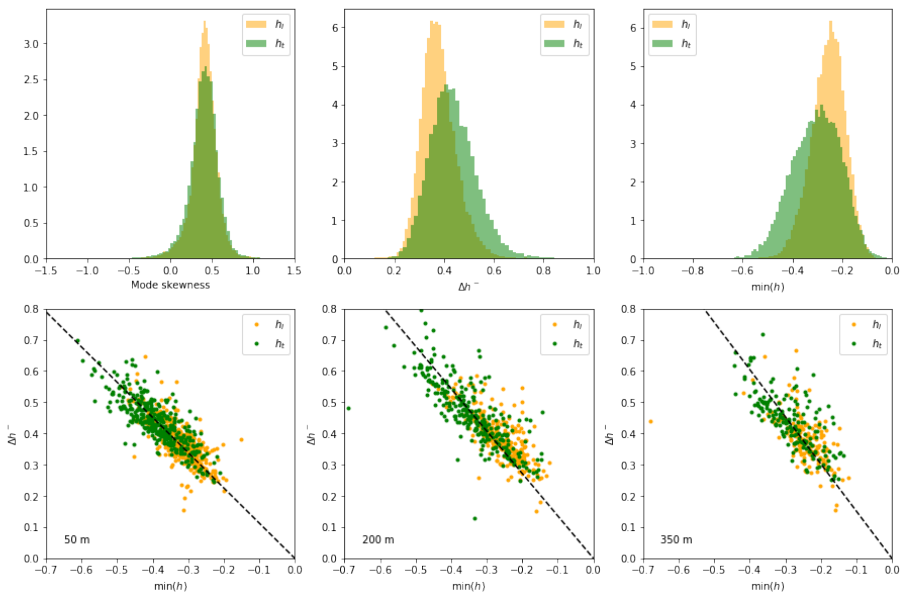

Figure 1: First row, from left to right, histograms of the skewness about de mode of the observed singularity exponents, the amplitude of the singularity spectra and most singular exponent. Second row, scatter plot between the amplitude of the singularity spectra and the most singular exponent at different depths. The black line corresponds to the line fitted to the data. h_l and h_t are the singularity exponents for the longitudinal and traverse components respectively.

Sample LaTeX abstract for talks and/or posters

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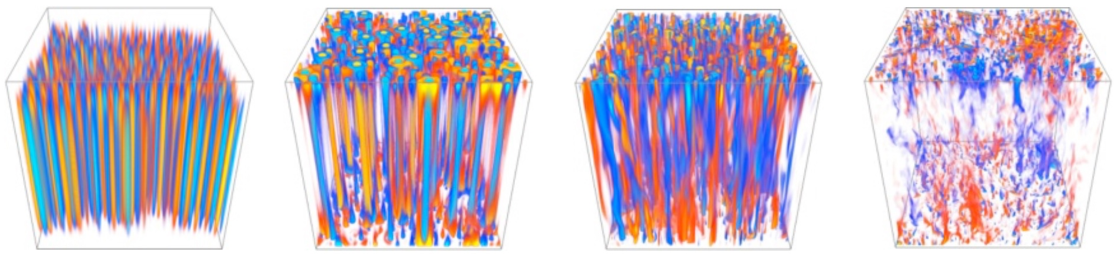
The majority of planetary and stellar bodies contain large volumes of low viscosity fluid that are stirred into turbulent motions by a variety of forces. Geostrophy, the balance between the rotational Coriolis force and the pressure gradient force, often appears as the dominant force balance at large scales rendering fluid motions rotationally constrained. While this balance often imposes a high-degree of stiffness to governing fluid equations, it also reveals the existence of slow manifolds within which dynamics of secondary importance are filter and simplified sets of reduced equations are valid. Such equations offer key theoretical insights and numerical simplifications that permit their execution in the extreme parameter regimes of geophysical and astrophysical fluid dynamics.

In this lecture, I will discuss the details involved in deriving quasigeostrophic systems of equations spanning from stably-stratified flows to unstably-stratified flows using asymptotic perturbation theory. A discussion of their impact will also be discussed.



Diffusion of inertia-gravity waves by geostrophic turbulence

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Inertia-gravity waves (IGWs) are ubiquitous in the ocean and the atmosphere. Once generated (by tides, topography, convection and other processes), they propagate and scatter in the large-scale, geostrophically-balanced background flow. In this study, we develop a theory that quantifies this scattering, and we verify its predictions through direct numerical simulations of the non-hydrostatic Boussinesq equations. The most effective scattering results from resonant interactions between two equal-frequency IGW modes and a flow (vortical, zero-frequency) mode. Since the wavevectors of equal-frequency IGWs make the same angle with the vertical, wave energy mostly remains on a cone defined by this angle in the three-dimensional wavevector space. Assuming low wave amplitudes, weak flow (small Rossby number) and a separation of spatial scales between waves and flow, we employ a WKB approach to derive a diffusion equation that describes the evolution of wave energy on this cone. The predictions of this diffusion equation agree remarkably well with simulations of the non-hydrostatic Boussinesq equations. The theory provides a time scale for the diffusion of waves and, in the stationary limit, predicts the scaling k^{-2} for the IGW energy spectrum. This scaling is consistent with atmospheric and oceanic observations in the range of scales where the preceding assumptions can be expected to hold.

Resonances in a simple spherical dynamo model

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Stars similar to the Sun demonstrate super-flares, which are considerably more powerful than solar flares. It is believed that the magneticfield energies of these stars are much higher than that of the Sun. The present study attempts to explain such an anomalously high magnetic energy by resonance phenomena related to the stellar dynamo, which involve significant changes in the behavior of the solutions subject to certain external effects and satisfy certain parametric relationships. These resonance phenomena are studied using low-mode models for a dynamo occurring in two or one spherical shells. It is shown that resonance effects arising in these models can result in increases of the magnetic energies by one and a half orders of magnitude compared with non-resonance cases. It is also shown that resonance dynamo conditions can differ considerably from the simple resonance conditions used for oscillating systems. This can probably be explained by the fact that the excitation and propagation of magnetic waves in dynamo problems are closely connected with each other, so that the resonance equations remain nonlinear even when they are maximally simplified.

We also investigate Earth-like dynamo with positive dynamo number. For a suitable parametric range the model demonstrates magnetic field excitation in form of vacillations, dynamo bursts and even stationary magnetic configurations. A resonance can be expected if magnetic field penetrates from one dynamo active shell into another or for a periodic modulation of dynamo drivers. In both cases we isolate some resonant phenomena mainly in the form of a resonant absorption. The results obtained are however quite remote from naive expectations and the problem seems to deserve a more extended investigation.

Nonlinear States in Stratified Shear Flows

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I[†] will discuss the recent efforts (Olvera & Kerswell 2017, Langham *et al.* 2019) to understand how stable stratification modifies the wealth of exact coherent structures (ECS) now known to exist in unstratified shear flows (such as plane Couette flow, channel flow and pipe flow). Adding stratification introduces two new parameters into the problem - the (bulk) Richardson number Ri_b measuring the imposed (stable) density difference imposed across the shear and the Prandtl number Pr - which then sit alongside the Reynolds number Re. Some questions I will try to address will be as follows. 1) Is there a threshold Ri_b above which ECS cannot exist? 2) Can new types of ECS exist because new types of wave motions are possible? And 3) what is the effect of Pr? In particular, can layering be found in these solutions for large Pr?

I will also touch upon some other recent work examining how the classic Kelvin-Helmholtz instability leads to finite-amplitude billows (Parker *et al.* 2019). This seems like such a well trodden area but there are still some surprises including a weak, possibly new type of linear instability found by accident.

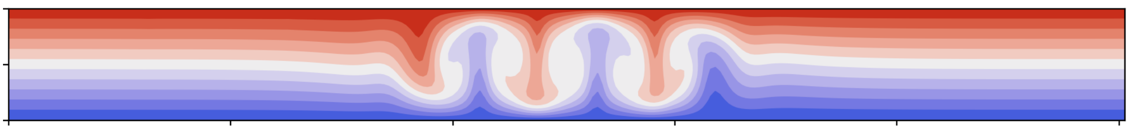

Figure 1: A spanwise-localized stratified steady flow state at $Pr = 2$ and $Re = 180$ in plane Couette flow - top (bottom) boundary is coming out of (into) the page using Dirichlet conditions for the density field (red/blue being less/more dense). The computational ratio of spanwise width to cross-stream height is 25:1 and has been reduced by about a half for this figure.

Langham, J., Eaves, T.S. & Kerswell, R.R. "Stably Stratified exact coherent structures in shear flows: the effect of Prandtl number" *arXiv:1904.04853*

Olvera, D. & Kerswell, R.R. "Exact coherent structures in stably-stratified plane Couette flow " *J. Fluid Mech.* **826**, 583-614, 2017.

Parker, J.P., Caulfield, C.P. & Kerswell, R.R. "Kelvin-Helmholtz billows above Richardson number 1/4" *arXiv:1905.04009*

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Salt-finger turbulence in two dimensions

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Abstract: A simple model of nonlinear salt-finger convection in two dimensions is derived and studied. The model is valid in the limit of a small solute to heat diffusivity ratio and a large density ratio, and so is relevant to both oceanographic and astrophysical applications. Two limits distinguished by the magnitude of the Schmidt number Sc are found. For Sc $\gg 1$, appropriate in an ocean setting, the model combines a prognostic equation for the solute field and a diagnostic equation for inertia-free momentum dynamics [1]. Two distinct saturation regimes are identified: a weakly driven regime, characterized by a large-scale flow associated with a balance between advection and linear instability, and a strongly-driven regime that produces multiscale structures, resulting in a balance between energy input through linear instability and energy transfer between scales. For Sc $= O(1)$, appropriate in some astrophysical situations, the same procedure leads to a modified Rayleigh–Bénard system with large-scale damping due to stabilizing temperature effects [2]. This system develops a horizontal jet structure that is maintained self-consistently by turbulent fluctuations, but coarsens over time. Depending on the driving strength the jet structure may exhibit relaxation oscillations or be statistically steady. In all cases the predicted one-dimensional spectra are in agreement with numerical simulations of the model equations. The effect of rotation about an axis inclined with respect to gravity is also studied [3].

[1] J.-H. Xie, B. Miquel, K. Julien and E. Knobloch. A reduced model for salt-finger convection in the small diffusivity limit. Fluids 2, 6:1–26 (2017).
[2] J.-H. Xie, K. Julien and E. Knobloch. Jet formation in salt-finger convection: a modified Rayleigh-Bénard problem. J. Fluid Mech. 858, 228–263 (2019).
[3] J.-H. Xie, K. Julien and E. Knobloch. Rotating salt-finger convection with small diffusivity ratio and large density ratio. Submitted.

Sample LaTeX abstract for talks and/or posters

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Earth's magnetic field is generated in its fluid metallic core through motional induction in a process termed the geodynamo. Fluid flow is heavily influenced by a combination of rapid rotation, Lorentz forces and buoyancy; it is believed that the inertial force and the viscous force are negligible. In such a system, the velocity and magnetic field organize themselves in a special manner, such that magnetic field B satisfies a solvability condition, known as Taylor's constraint. In this work, we solve this system using methods of optimal control to ensure that the required condition is satisfied all the time. We confine ourselves to axisymmetric case, and α effect is introduced to sidestep Cowling's anti-dynamo theorem. We also compare our results to a modified Taylor model, a term used by Roberts and Wu (2014), retaining an inertial term. This also introduces torsional oscillations. Extending this work to a 3D convective dynamo is in progress, and may also be presented at the workshop.

On the coalescence of anticyclones in stratified rotating flows

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Oceanic meso-scale lenticular vortices play an important role in the redistribution of momentum, heat, salt, nutrients and plankton in oceans and thus contribute to the climate equilibrium and ecological diversity on Earth. These vortices are governed by geostrophic and hydrostatic balances between pressure gradients, Coriolis and buoyancy forces from where they get their shape and aspect ratio [1, 2]. Their motions lead to a quasi-2D balanced dynamics that gives rise to quasi-geostrophic turbulence. Understanding the way energy escapes from this mesoscopic turbulence to feed the smallest oceanic scales where dissipation occurs, is the subject of an intense research. Among several different routes to dissipation, the emission of internal gravity waves has been evoked to be a possible conveyor of energy redistribution [3]. On another hand, vortex pairing events are observed in oceans [4] where they participate to the complex dynamics of the mesoscopic turbulence while generating fine filaments of vorticity as well as internal waves that could feed small dissipative scales. The aim of the present study is to describe and parametrize the merging of two lenticular anticyclones by means of stratified flow experiments performed on a rotating table. For this purpose, we generate pairs of anticyclonic vortices by the gentle injection of a small volume of water inside a continuously stably stratified rotating layer in a similar way that Griffiths and Hopfinger [5] did thirty years ago but for a two layer system. Figure 1 presents an example of a sequence of such a merging. To our knowledge, this problem has never been revisited experimentally for the case of lenticular vortices imbedded in a continuously stratified layer.

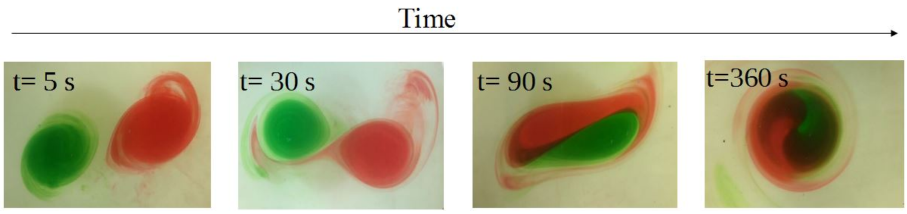

Figure 1: Temporal sequence of the merging of a pair of anticyclones for a Coriolis frequency $f = 1.57$ rad/s, a buoyancy frequency $N = 3.3$ rad/s and an initial separation $d_0 = 8$ cm.

Aside from describing the different regimes that lead or not to the coalescence of the pairs, in particular the determination of the critical initial separation distance as it has been done numerically using QG models [6] or non QG models at finite Rossby numbers [8], the final goal of this research will be to quantify the amount of ageostrophic energy loss when two lenticular vortices are coalescing. Indeed, during the transient time of their merging, the dipolar unbalanced structure that forms radiate away internal gravity waves as already observed in numerical simulations [7, 8].

References

[1] P. Hassanzadeh, P. S. Marcus, P. Le Gal, *The universal aspect ratio of vortices in rotating stratified flows: theory and simulation*, J. Fluid Mech. **706**, 4657, 2012.

[2] O. Aubert, M. Le Bars, P. Le Gal, P. S. Marcus, *The universal aspect ratio of vortices in rotating stratified flows: experiments and observations*, J. Fluid Mech. **706**, 3445, 2012.

[3] J.C. McWilliams, *Fluid dynamics at the margin of rotational control*, Environmental Fluid Mechanics, **8(5)**, 441-449, 2008.

[4] K.L.S. Tokos, H.H. Hinrichsen, W. Zenk, *Merging and migration of 2 meddies*, J. Phys. Oceanography **24 (10)**, 2129-2141, 1994.

[5] R.W. Griffiths, E.J. Hopfinger, *Coalescing of geostrophic vortices*, J. Fluid Mech. **178**, 73-97, 1987.

[6] D.G. Dritschel, *Vortex merger in rotating stratified flows*, J. Fluid Mech. **455**, 83-101, 2002.

[7] Á. Viúdez, *Spiral patterns of inertia-gravity waves in geophysical flows*, J. Fluid Mech. **562**, 73-82, 2006.

[8] J.N. Reinaud and D. Dritschel, *The merger of geophysical vortices at finite Rossby and Froude number*, J. Fluid Mech. **848**, 388-410, 2018.

Transition from inertial wave turbulence to geostrophic turbulence in rotating fluids - an experimental study

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A broad array of geophysical and astrophysical flows, be it in planetary cores, the Earth's ocean and atmosphere, or stellar interiors, are turbulent and strongly affected by rotation. These flows are very different from homogenous and isotropic turbulence owing to the presence of structures influenced by the Coriolis force and evolving on very different time scales. On one hand, the restoring effect of the Coriolis force leads to the existence of inertial waves that oscillate at frequencies smaller than or equal to twice the rotation rate. On the other hand, vortices aligned with the rotation axis and persisting over much longer time scales are also ubiquitously observed in rotating turbulence; they are associated to a balance between the pressure and Coriolis forces and are often called "geostrophic vortices". In the vast majority of rotating turbulence experiments and simulations, in which flows are excited by random fields, alternative jets or pairs of vortices, geostrophic eddies are dominant compared to inertial waves, the latter being advected and deformed by these persistent flows.

We propose to re-evaluate this standard observation via examining the turbulent saturation of parametric instabilities in rotating fluids, a problem of great interest for planetary and stellar interiors. Gravitational attraction exerted by other astrophysical bodies on a planet or a star produces a tidal deformation of its shape and causes periodic alterations of its rotation rate called librations. The combination of these two effects excites the resonance of two inertial waves at a precise frequency that eventually breaks down into turbulence. To reach this turbulent state, the forcing is very different compared to more classical works on rotating turbulence. First, energy is transfered to the flow only via a couple of inertial waves; besides, in the geophysical regimes we consider, both the forcing amplitude and dissipation are weak (*i.e.* both the Rossby and the Ekman numbers are small).

The experimental set-up we use to study the turbulent saturation of this inertial wave instability is designed to mimic tidal forcings in astrophysical bodies. An ellipsoidal container is mounted on a rotating table with a secondary motor forcing harmonic perturbations of the mean rotation rate. We characterise the turbulent saturation flow with particle image velocimetry (PIV). With temporal analysis of the velocity fields, we show that at the lowest forcing amplitudes, the resonant waves excite daughter waves with different frequencies via non-linear resonant interactions. Conversely, at large forcing amplitudes, the resonant waves force a more classical geostrophic turbulence where the flow is dominated by strong vortices.

Our study suggests that, in the regimes of low forcing amplitude and dissipation, it is possible to excite an inertial wave turbulence, *i.e.* a flow with many waves that are non-linearly, resonantly, interacting. It is the first time a transition between a wave-dominated and a geostrophic-dominated regime is observed experimentally. This result has strong implications for instance on tidal dissipation and dynamo action in planets and stars. In particular, generation of a magnetic field by a set of inertial waves has seldom been considered and remains to be studied in detail.

Excitation of Internal Gravity Waves by Convection

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Almost all stars have both convective and stably-stratified radiative regions. The convection can relatively efficiently excite internal gravity waves which propagate in the stably-stratified regions. These waves can then transport chemical species, energy, and angular momentum, leading to observable changes in stellar properties. Here I will describe a theoretical approach to the wave generation problem, popularized by Lighthill for the excitation of sound waves by turbulence. I will also describe the latest simulations of wave excitation, providing some evidence in favor of this theory.

Tidally-generated internal waves and mixing in the ocean

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Oscillatory tidal flow over sea-floor topography in a density-stratified ocean leads to the generation of internal waves. When these waves break, the resulting turbulence mixes heat and salt across density surfaces. This tidally-driven mixing in the stratified ocean interior is an important component of the large-scale ocean overturning circulation. I will outline the theory of tidal generation of internal waves, both propagating waves at the tidal frequency and transient lee-waves, beginning with linear theory and extending into nonlinear regimes, particularly for topographic steepness. The processes by which internal waves can lead to mixing, including transient hydraulic jumps and shear instability of small-scale waves will be explored. Finally, I will briefly describe current parameterizations of tidally-driven mixing in ocean climate models.

Experimental and numerical study of Jupiter's deep-seated zonal jets: formation, dynamics and long-term evolution

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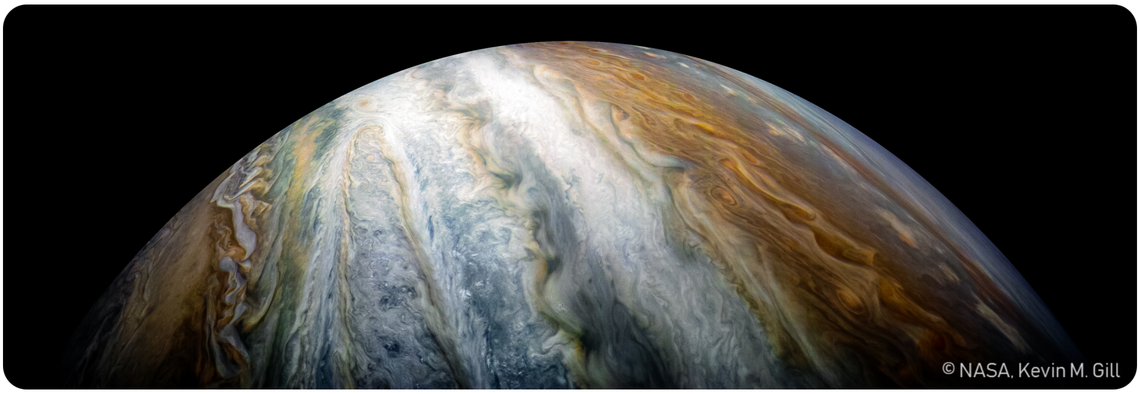

The stability, size and dynamics of Jupiter's zonal jet streams is still a poorly understood aspect of its rich tropospheric dynamics, especially in terms of coupling with the gas giant's interior. Recently, inversion of Juno spacecraft gravity measurements has shown that the Jovian jets extend to about 3,000 kilometers beneath the clouds inside the liquid mantle [1,2], thus supporting a deep model for Jupiter's jet streams in opposition to a shallow-layer model where the jets would be restricted to a thin gaseous region of $\sim$100 km, near the cloud level of Jupiter.

Here, we address the question of deep-seated zonal jets formation and long-term evolution by coupling laboratory experiments and idealized numerical simulations. Experimentally, based on [3], a strong topographic β-effect is obtained inside a rotating water tank thanks to the paraboloidal free surface due to the centrifugally-induced pressure. The shape of the bottom of the tank is chosen so that this β-effect is spatially constant. A turbulent forcing is performed over 128 injection and suction points at the base of the tank allowing a control of its spatial distribution and intensity. Time-resolving PIV measurements are performed in horizontal and vertical planes. Numerically, based on a simplified set of two dimensional equations valid in the limit of rapid rotation (so-called quasi-geostrophic model), we perform systematics simulations modelling the experiment for a low numerical cost. We show the generation of deep-seated zonal flows whose kinetic energy spectra are consistent with theoretical predictions in the regime of so-called zonostrophic turbulence [4]. Additionally, we systematically study the effect of the small-scale excitation on the dynamics and radial migration of the jets.

[1] Kaspi, Y., Galanti, E., Hubbard, W., Stevenson, D., Bolton, S., Iess, L., Guillot, T., Bloxham, J., Connerney, J., Cao, H., et al. Jupiter's atmospheric jet streams extend thousands of kilometres deep. *Nature*, 555(7695):223, 2018.
[2] Guillot, T., Miguel, Y., Militzer, B., Hubbard, W., Kaspi, Y., Galanti, E., Cao, H., Helled, R., Wahl, S., Iess, L., et al. A suppression of differential rotation in jupiter's deep interior. *Nature*, 555(7695):227, 2018.
[3] Cabanes, S., Aurnou, J., Favier, B., and Le Bars, M. A laboratory model for deep-seated jets on the gas giants. *Nature Physics*, 13(4):387, 2017.
[4] Galperin, B., Sukoriansky, S., and Dikovskaya, N. Geophysical flows with anisotropic turbulence and dispersive waves: flows with a β-effect. *Ocean Dynamics*, 60(2):427–441, 2010.

Astrophysical discs: from accretion theory to high resolution observations.

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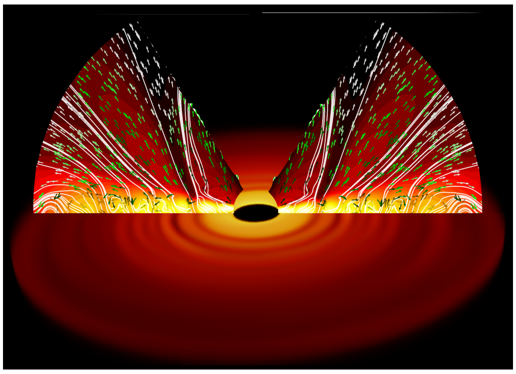
In this lecture, I will introduce our current understanding of astrophysical disc dynamics. Starting from the basic principles of mass and angular momentum conservations, I will show how we believe these discs are responsible for the accretion of gas onto their central object (young star, black hole...). I will then discuss several hydrodynamical and magneto-hydrodynamical mechanisms susceptible to affect accretion in these discs, and I will apply them in the context of discs around young stars, known as protoplanetary discs. I will also discuss some observational tests which are currently used to discriminate between accretion scenarios.



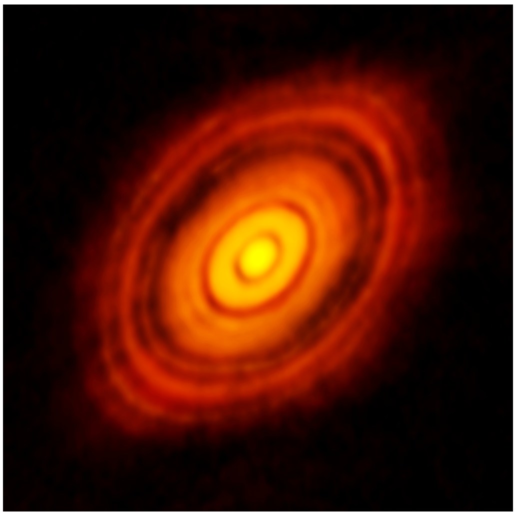


Figure 1: Left: numerical model of a protoplanetary disc (Béthune et al. 2017), Right: high resolution observation of the disc around HL-Tau by the ALMA observatory (ALMA partnership et al. 2015).

Inertial waves in spherical shells

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It is well-known that the inertial wave problem in a spherical shell is ill-posed and thus inviscid smooth modes usually do not exist. Inertial waves are in the form of thin conical shear layers attached to the characteristics spherical shells by taking into account the viscosity. Using high resolution numerical calculation at very low Ekman numbers, we show that there may exist large scale smooth structures hidden underneath the thin conical shear layers at certain frequencies. These large scale structures are responsible for the resonant peaks when solving the forced inertial waves problem (e.g. tidally forced inertial waves), which are not dissimilar to the inertial modes in a full sphere.

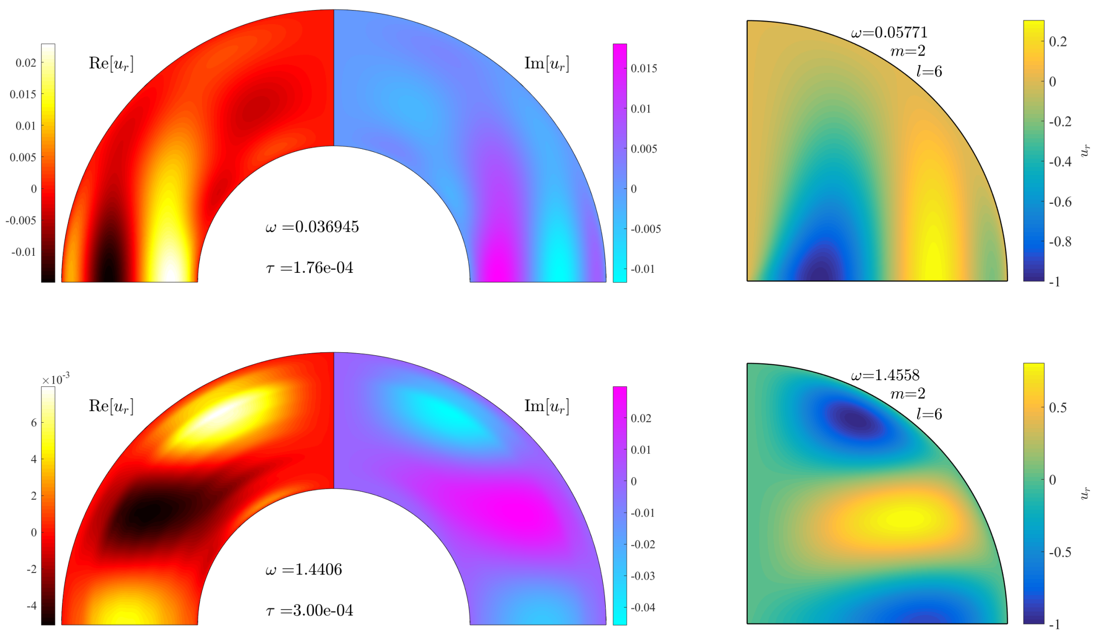

Fig. Large scale structures of some eigen modes in a spherical shell and the corresponding inertial modes in a full sphere.

A Generalized Mixing Length for Eddy-Diffusivity Mass-Flux Models of Boundary Layer Turbulence and Convection

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Because of the limited spatial resolution of numerical weather prediction and climate models, they have to rely on parameterizations to represent atmospheric turbulence and convection. Historically, largely independent approaches have been used to represent boundary layer turbulence and convection, neglecting important interactions at the subgrid scale. Here we further develop an eddy diffusion/ mass flux (EDMF) scheme that represents all subgrid-scale mixing in a unified manner, partitioning subgrid-scale fluctuations into contributions from local diffusive mixing and coherent advective structures and allowing them to interact within a single framework.

The EDMF scheme requires closures for the interaction between the turbulent environment and the plumes and for local mixing. A second-order equation for turbulence kinetic energy provides one ingredient for the diffusive local mixing closure, leaving a mixing length to be parameterized. A new mixing length formulation is proposed, expressing local mixing in terms of the same physical processes in all regimes of boundary layer flow, from stable to convective boundary layers. The formulation is tested across a wide range of boundary layer regimes, including a stably stratified boundary layer, shallow cumulus convection, and the stratocumulus-topped marine boundary layer. Comparison with large eddy simulations (LES) shows that the EDMF scheme with this diffusive mixing parameterization accurately captures the structure of the boundary layer in all the cases considered.

Radiatively driven convection

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Buoyancy driven turbulent flows pertain to numerous geo- and astrophysical systems, where they have far reaching consequences: understanding them in atmospheric and oceanographic context is of paramount importance for climate modelling; in planetary and stellar cores, they control magnetic field generation via the dynamo effect, to cite a few examples. Experimentally, convective flows have often been driven by heat fluxes from the boundaries. This setup is conducive to the formation of boundary layers that throttle the heat transfer, resulting in a diffusivity-controlled heat transfer, even for a turbulent bulk: $\mathrm{Nu} \sim \mathrm{Ra}^{1/3}$ (Malkus 1954). By contrast, when heat is deposited directly in volume, thereby by-passing boundary layers, a recent experiment (Lepot 2018) has evidenced an inviscid heat-transfer regime (sometimes referred to as the "ultimate regime" or the "mixing length regime"): $\mathrm{Nu} \sim \mathrm{Ra}^{1/2}$. In this experiment, dyed water is heated through a transparent bottom by means of a powerful spotlight. Further, the transition between the two regimes has been analyzed when the typical depth of injection of heat varies (Bouillaut 2019).

I will briefly summarize those recent experimental results, and will complement them with a numerical study of the Boussinesq equations of motion performed with the HPC solver *Coral*. In particular, the influence of the Prandtl number (intimately linked to the fluid and therefore tuned with difficulty in experiments) will be discussed, and two distinct regimes will be decribed for low and high Prandtl number values. Finally, I will comment on the influence of rotation, a key ingredient of natural flows.

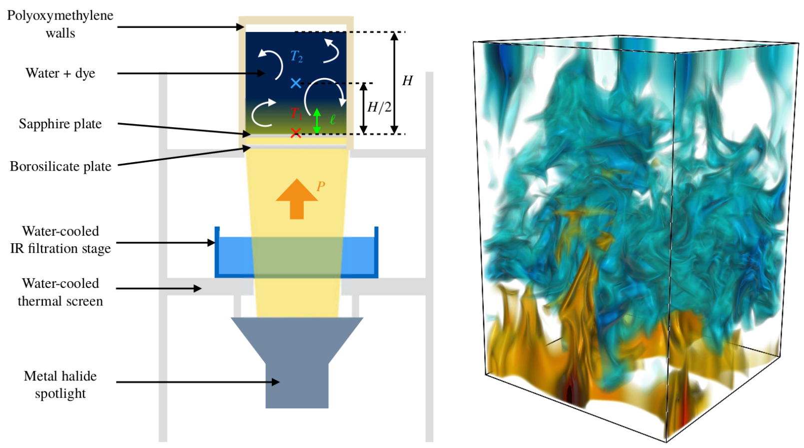

Figure 1: Left: Experimental setup used in Lepot (2018) and Bouillaut (2019). Right: volume rendering of a characteristic temperature field obtained in a DNS of radiatively driven convection (*Coral* code).

References:

W.V.R. Malkus, The heat transport and spectrum of thermal turbulence, *Proc. R. Soc. Lond. A*, 225 (1954)
S. Lepot, S. Aumaitre, B. Gallet, Radiative heating achieves the ultimate regime of thermal convection, *Proc. Natl. Acad. Sci.*, 115 (2018)
V. Bouillaut, S. Lepot, S. Aumaitre, B. Gallet, Transition to the ultimate regime in a radiatively driven convection experiment, *J. Fluid Mech.*, 861, R5 (2019)
Coral is available upon request at the URL: `https://bitbucket.org/benmql/coral`

Responses of Wave-Induced Mixing in the Southern Ocean to Changes in Large-Scale Atmospheric Circulation

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The Southern Ocean plays a key role in regulating global climate since it absorbs heat and atmospheric carbon. However, mixed layer depth there is significantly underestimated in some models which implies that representations of upper ocean mixing is not adequate. In this respect, a number of recent studies suggests that the role of surface wind waves is not properly accounted for. Dynamical controls on local wave climate in the Southern Ocean are still poorly understood since it is driven by winds resulting from the superposition of numerous low-frequency atmospheric circulation modes. Here we dynamically force a spectral wave model with a set of idealized atmospheric circulations from an AGCM thus varying the behavior of tropospheric jet streams and large-scale overturning cells. We do this through perturbations applied to mid-latitude and tropical SST. We investigate the wave impact on the mixed layer using parameterizations of nonbreaking-wave-induced mixing as well as effects of the Stokes drift and in particular Langmuir turbulence. With tropical winter warming, Hadley circulation expands along with a shift in jet stream intensity and latitude. This leads to a large shift ($> 10\,^{\circ}$ lat) in location and increase in the magnitude of the largest wind waves. In summer, tropical warming leads to moderate changes in wind stress magnitude while only the most extreme warming scenarios result in poleward jet and wave maxima shifts. With mid-latitude warming, the Southern Annular Mode weakens and westerlies move equatorward. In both set of experiments, wave-induced mixing increases in kind with the meridional temperature gradient. In general, quasi-linear patterns in surface stress changes result in non-linear responses in wave heights and the corresponding wave-induced vertical mixing. Thus, we demonstrate that changes to the dynamics of the Southern Ocean surface boundary layer with shifting westerlies and under tropical expansion must be to a large extent accounted by the role of ocean wind waves.

Rotating spherical convection under the influence of an imposed magnetic field

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The geomagnetic field is thought to exert a strong influence on the dynamics of the outer core. Modelling the magnetically-dominated convection regime in self-sustained dynamos is challenging numerically as it requires low Ekman numbers or large magnetic Prandtl numbers. Here we will study this regime through the use of magnetoconvection simulations in a rotating spherical shell, in which an imposed uniform axial field interacts with convective flows to induce an additional field. Gradually increasing the strength of the imposed field allows us to determine the conditions under which the magnetic forces affect the dynamics of the flow. We will show how the flow structures and heat transport are modified in the presence of the field.

Morphology and transitions in rapidly rotating planetary cores

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In numerical simulations of planetary dynamos there is an abrupt transition in the dynamics of both the velocity and magnetic fields at a 'local' Rossby number of 0.1. For smaller Rossby numbers there are helical columnar structures aligned with the rotation axis, which efficiently maintain a dipolar field. However, when the thermal forcing is increased, these columns break down and the field becomes multipolar. Similarly, in rotating turbulence experiments and simulations there is a sharp transition at a Rossby number of ~ 0.4. Again, helical axial columnar structures are found for lower Rossby numbers, and there is strong evidence that these columns are created by inertial waves, at least on short timescales. We perform direct numerical simulations of the flow induced by a layer of buoyant anomalies subject to strong rotation, inspired by the equatorially biased heat flux in convective planetary dynamos. We assess the role of inertial waves in generating columnar structures. At high rotation rates (or weak forcing) we find columnar flow structures that segregate helicity either side of the buoyant layer, whose axial length scale increases linearly, as predicted by the theory of low-frequency inertial waves (figure 1: R1). As the rotation rate is weakened and the magnitude of the buoyant perturbations is increased, we identify a portion of the flow which is more strongly three-dimensional (figure 1: R3 & R5). We show that the flow in this region is turbulent, and has a Rossby number above a critical value $Ro^{crit} \sim 0.4$, consistent with previous findings in rotating turbulence. We suggest that the discrepancy between the transition value found here (and in rotating turbulence experiments), and that seen in the numerical dynamos ($Ro^{crit} \sim 0.1$), is a result of different definitions of the perpendicular integral length scale $\ell_\perp$ used to define $Ro = u/2\Omega\ell_\perp$. This in turn suggests that inertial waves, continually launched by buoyant anomalies, sustain the columnar structures in dynamo simulations, and that the transition documented in these simulations is due to the inability of inertial waves to propagate for $Ro > Ro^{crit}$ (McDermott & Davidson 2019).

McDermott, B. R. & Davidson, P. A. 2019 A physical mechanism for the dipolar-multipolar dynamo transition. Submitted to *Journal of Fluid Mechanics*.

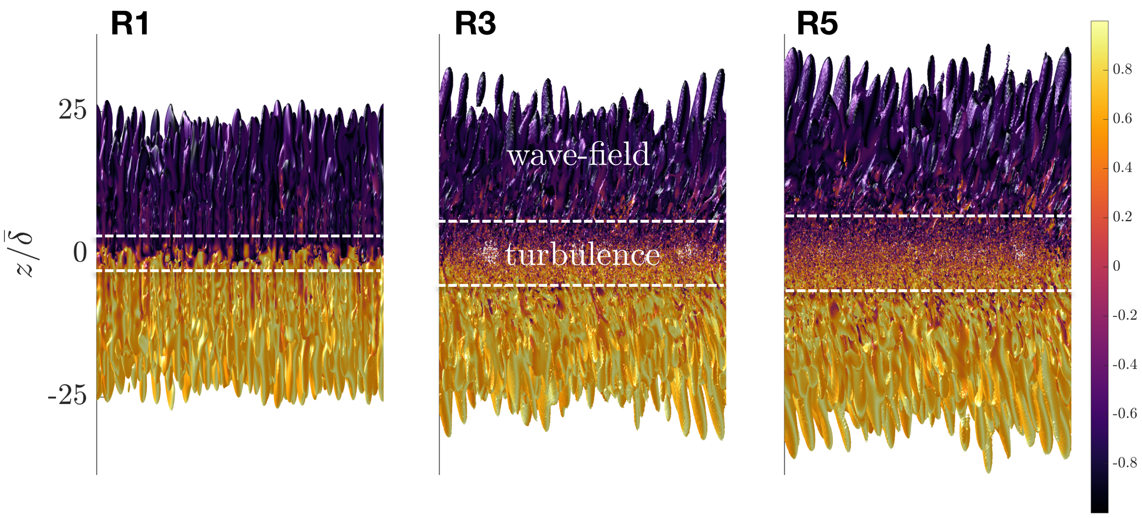

Figure 1: Vorticity coloured by relative helicity for three of our runs (of increasing Ro): R1, R3 and R6. We identify a turbulent region in the centre of the box (delineated by dashed lines), surrounding the layer of buoyancy.

Latest Comparisons of Experimental Results and High Performance Non-Linear Numerical Simulation on Stratified Rotational Instabilities

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Understanding the mechanisms that can result in an outward transport of angular momentum is a central problem regarding astrophysical objects formation, particularly in the theory of accretion discs [1]. Among other candidates, the Strato Rotational Instability (SRI) has attracted attention in recent years as a possible instability leading to turbulent motion in these systems. The SRI is a purely hydrodynamic instability consisting of a classical Taylor-Couette (TC) system with stable density stratification due to, for example, salinity or a vertical temperature gradient.

Many information about the SRI can be obtained from numerical simulations and particularly designed laboratory experiments of axially-stratified TC setups, as the one in the BTU laboratory.

For obtaining a stable density stratification along the cylinder axis, the bottom lid of the setup is cooled, and its top part is heated, establishing axial linear temperature profiles varying between 3K and 5K. The inner and outer cylinders on the experimental setup rotate independently, with different angular veocities. The experimental results presented were obtained at different values of rotation ratio of $\mu = \Omega_{out}/\Omega_{in}$, where Ω is the angular velocity of the cylinder, and for different Reynolds numbers. More details about the experimental setup can be found in [2].

The experimental velocity profiles are obtained using *Particle Image Velocimetry* (PIV), with the camera co-rotating with the outer cylinder. The PIV measurements absolute error is of less than 2%, and all experiments were repeated at least 2 times at different days, so that the result's reproducibility could be guaranteed.

High performance parallel numerical simulations using the same configuration as the BTU experiment have been developed at the M2P2 laboratory at the Aix-Marseille University (AMU), and at the LAMPS laboratory at the University of Perpignan. The code solves the non-linear Navier-Stokes equations under the Boussinesq approximation. Details of the numerical scheme and the parallelization can be found in [3] and [4].

Latest comparisons of the experimental results with numerical simulations did show good agreements when compared qualitatively and quantitatively, regarding velocity profiles, and the analysis of the SRI frequencies in Fourier space.

References

[1] P J Armitage. *Astrophysics of planet formation.* Cambridge University Press, 2010.

[2] T Seelig, U Harlander, and M Gellert. Experimental investigation of stratorotational instability using a thermally stratified system: instability, waves and associated momentum flux. *Geophysical & Astrophysical Fluid Dynamics*, 112(4):239–264, 2018.

[3] S Abide, M S Binous, and B Zeghmati. An efficient parallel high-order compact scheme for the 3d incompressible navierstokes equations. *International Journal of Computational Fluid Dynamics*, 31(4-5):214–229, 2017.

[4] S Abide, S Viazzo, I Raspo, and A Randriamampianina. Higher-order compact scheme for high-performance computing of stratified rotating flows. *Computers & Fluids*, 174:300–310, 2018.

Acknowledgement

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Precessing flow in a spheroid

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The flow in the liquid core of the Earth plays an important role in the exchanges between the core and the mantle and is also the source of the magnetic field. An important part of its energy comes from the precession of the Earth, which is able to drive complex flows in the outer core.

The base flow of precession obtained theoretically by Poincaré (1910) for an inviscid fluid and by Busse (1968) for a viscous fluid is a solid body rotation, where the axis of rotation can differ notably from the axis of rotation of the Earth. For a sufficient forcing, the fow becomes more complex because of the eruptions of the Ekman layer (Bondi & Littletown 1953) and due to instabilities which can modify the flow in the bulk (Le Bars et al. 2015). Finally, the spheroidal shape of the Earth modifies the base flow and can also trigger several other instabilities (Kerswell 1993). Three different instabilities have been predicted theoretically but some of them have not yet been observed experimentally.

I will present experimental measurements obtained in the idealized case of a precessing spheroid. The flow is visualised with flat reflective particles, which allows a study over a broad range of parameters. The flow is then accurately characterised with PIV measurements.

For retrograde precession, the measurements of the mean flow show an hysteretic cycle between two branches of solutions around the singularity of the inviscid solution of Poincaré (1910). This subcritical bifurcation is correctly predicted by the viscous theory (Busse 1968).

These two solutions show two transitions to turbulence when the Ekman number decreases. Both transitions are due to instabilities where inertial modes are coupled by a triadic resonance. The first instability is similar to the one described in a precessing sphere and called Conical Shear Instability (CSI) by Lin et al. (2015). The second instability presents the characteristics of the CSI with inertial modes of low azimuthal wave number but also the characteristics of the elliptic instability (Lacaze et al. 2004). Finally, a third region of instability is observed and measured in the case of prograde precession around a characteristic precession frequency where the inviscid base flow does not present any singularity.

Extrapolating the instability thresholds for the first two instabilities indicates that the flow in the outer core of the Earth is stable. However, unstable conditions could exist for other planets or satellites with liquid cores. Finally, the third instability observed in the prograde precession could happen for the Earth.

Analogy between viscoelastic hydrodynamics and Magnetohydrodynamics

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The analogy between viscoelastic instability in the Taylor-Couette flow and the magneto-rotational instability (MRI) has been established by Ogilvie and coworkers in two papers [1, 2] in the limit of infinite relaxation time of polymer solution and of vanishing magnetic diffusivity. However these limit cases cannot be achieved in any experiment, so that recent experimental results by Boldyrev et al.[3]and by Bai et al. [4] cannot be satisfactory interpreted in the framework of Ogilvie's work. In a recent work [5], we have shown that the Oldroyd-B model for viscoelastic fluids can be written in terms of magnetic-like fields which satisfy a set of Maxwell-like equations. In the limit of infinite relaxation time for the polymer solution, the polymeric stress tensor is analogue of the Maxwell stress tensor of a magnetic field. Away from this asymptotic case, the decomposition of the polymer stress tensor into a tensor product of magnetic-like field is no more unique. However, the analogy between the Oldroyd-B model and the Maxwell's equations stills holds if one introduces three magnetic-like fields obeying Maxwell's equations with magnetic currents and charges. This is related to the existence of a gauge symmetry of Oldroyd-B model. We present three choices of gauge symmetry and the corresponding viscoelastic fields for the viscoelastic Taylor-Couette flow. This model opens new perspectives for the extension of the analogy between Magnetohydrodynamics (MHD) and viscoelastic hydrodynamics; the latter being much more accessible to experimental investigation.

References

[1] G.I. Ogilvie and M.R.E. Proctor, *J. Fluid Mech.***476**, 389-409 (2003).

[2] G.I. Ogilvie and A.T. Potter, *Phys.Rev. Lett.***100**, 074503(2008).

[3] S. Boldyrev, D. Huynh and V.Pariev, *Phys.Rev. E.***80**, 066310(2009).

[4] Y. Bai, O. Crumeyrolle and I. Mutabazi, *Phys. Rev. E* **92**,031001(2015).

[5] T. Vieu and I. Mutabazi, accepted in *J. Fluid Mech* (2019).

Inertial Waves and Inertial Modes in Planets

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In this lecture, I will introduce Inertial Waves and Inertial Modes that exist in a rapidly rotating fluid layer such as a planetary core or subsurface ocean. The outline of my lecture will be as follow:

1. Lecture I: Introduction to rapidly rotating fluids:

   Some observations.

   Navier-Stokes in a rotating frame.

   Taylor-Proudman Theorem.

   Earths core and Mantle.

2. Lecture II: Inertial Waves and Inertial Modes

   Some observations.

   Inviscid Inertial Waves.

   Inviscid Inertial Modes.

   Viscous Correction.

   Resonances, large flows from small perturbations.

   The Poincaré mode.

3. Lecture III: Instabilities.

   Some observations.

   Parametric Instabilities.

   Boundary Layer instabilities.

   The case of the Lunar core.

4. Lecture IV: Transfer of angular momentum and energy in rapidly rotating fluids.

   In this lecture I will present the results obtained by F. Burman during his Phd on the transfer of energy and angular momentum by inertial waves generated by a topography at the walls.

Eye formation in large scale vortices: idealised models vs actual tropical cyclones

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One of the most striking features of atmospheric vortices, such as tropical cyclones, is that they often develop a so-called eye: a region of reversed flow in and around the axis of the vortex. The key dynamical processes for this structure are still poorly understood. The ubiquitous appearance of eyes embedded within large-scale vortices suggests that the underlying mechanism by which they first form may be independent (partially if not wholly) of complexities such as the stratification or moist convection. To put the idea of a simple hydrodynamic mechanism to the test we considered what is, perhaps, the simplest system in which eyes may form; that of steady axisymmetric convection in a rotating Boussinesq. Our numerical experiments show that in this configuration, for sufficiently vigorous flows, an eye can form. I will first discuss the mechanism of eye formation and the criteria required for eye formation in this idealised Fluid Mechanics model. I will then discuss the robustness of this mechanism. I will present more realistic models of tropical cyclones (involving more realistic descriptions of the atmosphere), and investigate the validity of our assumptions.

References:
L. Oruba, P. A. Davidson, E. Dormy, 2017, *J. Fluid Mech.*, **812**, 890-904.
L. Oruba, P. A. Davidson, E. Dormy, 2018, *Phys. Rev. Fluids*, **3**, 013502.

Shear instabilities in stratified-rotating fluids: effects of strong thermal diffusion and non-traditional f-plane

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Stability of horizontal shear flows in vertically-stratified and rotating fluids has been an important research topic in geophysical and astrophysical fluid dynamics. In stellar radiative zones, the thermal diffusion is high with very small Prandtl number $Pr = \nu/\kappa$, the ratio between the kinematic viscosity ν and the thermal diffusivity κ which varies between 10^{-6} and 10^{-9} (Liginières 1999). Also, the rotation component in latitude direction is often neglected (i.e. the traditional f-plane approximation) but it modifies dynamics of inertial-gravity waves in stellar interiors (see e.g. Gerkema *et al.* 2008, Mathis *et al.* 2014). However, the high thermal diffusivity and the non-traditional f-plane approximation have not been well considered in the study of shear flow instability despite of its crucial importance in astrophysical context.

In this study, we consider a canonical example of the horizontal shear flow in a hyperbolic tangent profile: $U(y) = U_0 \tanh(y/L)$ (U_0: reference velocity, L: length scale), and a linear stability analysis is performed in the presence of stratification, rotation, and thermal diffusivity. We first study the shear instability on the traditional f-plane where the rotation is aligned with the vertical axis. For the hyperbolic tangent shear profile, two types of instabilities are known: a shear instability due to the inflection point and an inertial instability. While the inflectional shear instability can be observed in any values of stratification and rotation, the inertial instability is only present in the range $0 < f < 1$ where f is the dimensionless Coriolis parameter. We found that as the thermal diffusion becomes strong (i.e. as the Péclet number $Pe = U_0 L/\kappa$ tends to 0), the inflectional shear instability stabilizes while the inertial instability destabilizes (figure 1a). The destabilization of the inertial instability can be explained by means of the WKBJ approximation. We also observed that there is a similarity relation of the shear instability in thermally-diffusive and strongly-stratified fluids if the rescaled parameter $Pe^{-1}N^{-2}$ is applied (figure 1b) where N is the dimensionless Brunt-Väisälä frequency. On the non-traditional f-plane, we found that both the inflectional and inertial shear instabilities are strongly modified due to the horizontal rotation component f_h. More detailed results about effects of strong thermal diffusion and non-traditional f-plane on the shear instability will be discussed in the presentation.

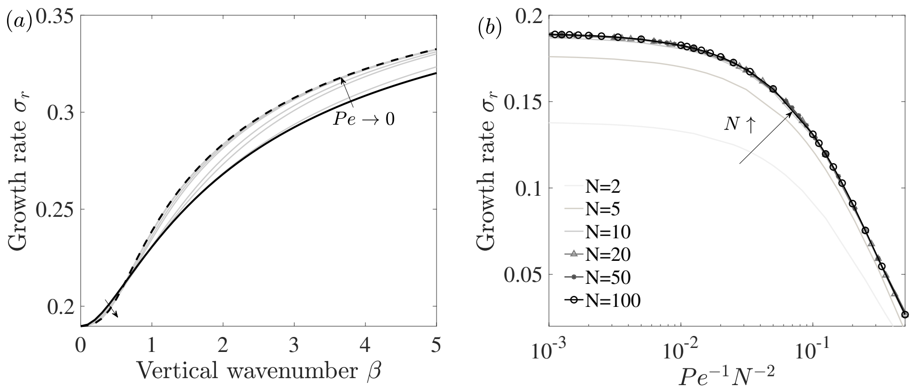

Figure 1: (a) An example of linear stability analysis result: growth rate versus vertical wavenumber for shear flows in stratified-rotating fluids for different Péclet numbers: growth rate curves (black and gray solid lines) tends to the curve from the unstratified case (black dashed line) as Péclet number decreases. (b) Self-similarity observed in thermally-diffusive and strongly-stratified fluids for the shear instability.

Collision of cloud droplets settling in turbulent atmosphere

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Major source of uncertainty in predicting precipitation formation comes from the absence of reliable theoretical predictions for the collision rate of cloud droplets. The calculation of the collision rate constant for hydrodynamically interacting finite Stokes droplets sedimenting in a turbulent atmosphere is an open problem in the area of cloud microphysics (see Grabowski and Wang, 2013), which may explain the *condensation-coalescence bottleneck* in warm rain formation. We calculate the collision rate constant of hydrodynamically interacting inertialess droplet pairs sedimenting in a turbulent atmosphere in the rapid settling limit, where the Kolmogorov time scale is much larger than the time taken for a droplet to settle across an eddy. In other words, we investigate the dynamics of pairs for Stokes number, $St_\eta = \tau_v/\tau_\eta << 1$ and the settling parameter, $Sv_\eta = g\tau_v/u_\eta >> 1$, where g is the acceleration due to gravity, τ_v is the particle viscous relaxation time, τ_η and u_η are the Kolmogorov time and velocity scales, respectively. Because of the sub-Kolmogorov droplet sizes, we approximate the fluid motion in the vicinity of a pair of droplets as a locally linear flow with the fluctuating velocity gradient that appears from the background turbulent flow. The response of the relative droplet position is small over the correlation time of the flow and therefore, a diffusive process characterizes the relative droplet motion with diffusivity D^H_{ij}. Hydrodynamic interactions lead to a non-solenoidal relative velocity between the droplet pair. The compressibility of relative velocity between the particle pair causes a net drift,V^H_i, toward small interparticle separations. The drift-diffusion fluxes are calculated from velocity gradient autocorrelation function along the settling trajectory. The Fokker-Planck equation for pair probability density function, $P(\mathbf{r}, t)$, that describes the probability of finding particles separated by the vector $\mathbf{r}$ at time t, is derived in terms of D^H_{ij} and V_i and then solved numerically. This V_i contains relative drift, V^H_i, and relative velocity due to differential settling, V^R_i. Collision rate constant is calculated by integrating the flux of pair probability at the collision surface and it is found more than that of pure turbulent flow case which was calculated by Burnk et al. 1997, 1998. Important equations are given below:

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial r_i}\left[\left(V^H_i + V^R_i\right)P - D^H_{ij}\frac{\partial P}{\partial r_j}\right] = 0 \tag{1}$$

$$V^H_i = -\int_{-\infty}^{t}\left\langle w_i(\mathbf{r}(t), \mathbf{x}(t), t)\frac{\partial w_l}{\partial r_l}(\mathbf{r}(t'), \mathbf{x}(t'), t')\right\rangle dt' \tag{2}$$

$$D^H_{ij} = \int_{-\infty}^{t}\langle w_i(\mathbf{r}(t), \mathbf{x}(t), t) w_j(\mathbf{r}(t'), \mathbf{x}(t'), t')\rangle\, dt' \tag{3}$$

$$V^R_i = (\gamma\lambda^2 - 1)\mathrm{U}^{\mathsf{S}}_k\left\{L(s)\frac{r_i r_k}{r^2} + M(s)\left(\delta_{ik} - \frac{r_i r_k}{r^2}\right)\right\} \tag{4}$$

$$w_i = \Gamma_{il} r_l - \left\{A(r)\frac{r_i r_k}{r^2} + B(r)\left(\delta_{ik} - \frac{r_i r_k}{r^2}\right)\right\} S_{kl} r_l \tag{5}$$

where $\Gamma_{il}(t)$ is the statistically stationary fluctuating velocity gradient and $S_{kl}(t)$ is the rate of strain defined as $\frac{1}{2}(\Gamma_{kl} + \Gamma_{lk})$. A and B are the mobility functions for two hydrodynamically interacting spherical particles in a linear flow field and those due to settling under gravity through a quiescent fluid are denoted by L and M(see Batchelor & Green 1972 and Batchelor 1982). A, L are the axisymmetric mobilities (i.e. mobility functions due to the relative motion along the line-of-centres) and B, M is asymmetric mobilities (i.e. mobility functions due to relative motion normal to the line-of-centres). All these mobilities depends on radii-ratio, $\lambda = a_2/a_1$, and non-dimensional centre-to-centre distance between the spherical particles, $s = 2r/(a_1+a_2)$. $\mathrm{U}^{\mathsf{S}}_k = 2a_1^2(\rho_1 - \rho_f)g_k/9\mu$ is the sedimentation velocity of particle 1 and $\gamma = (\rho_2 - \rho_f)/(\rho_1 - \rho_f)$. where ρ_f and μ are the fluid density and viscosity respectively. $\mathbf{g}$ is the acceleration due to gravity.

Numerical and experimental modeling of two-phase change in large-scale rapidly rotation convection

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In a world where climate change is causing increases in extreme weather, accurate weather prediction is a primary concern for people and governments hoping to adapt to changing conditions. Numerical Weather Prediction (NWP) is a powerful field for predicting and modeling atmospheric systems. Further development of NWP techniques for large weather systems is a relevant venture in the field of atmospheric modeling. One such improvement could be made by advancing the ability to model phase change during large-scale rapidly rotating convection. In order to compare numerical models with observations, the phase change between vapor and solid will be modeled numerically and experimentally. Experimentally, this can be achieved using iodine gas in a convective cell.

Initially, a fast autoconversion and rain evaporation model will be numerically solved and compared with the full partial differential equations. Comparisons between the full model and a reduced model valid for rapid rotation will be carried out utilizing Dedalus Project spectral method software (dedalus-project.org). This model is then adjusted to accurately model vapor and solids in order to compare with experiments. The resulting model will also be formulated in the rapidly rotating limit.

The experimental component of this investigation will involve a rotating canister of iodine gas heated from below and cooled from above. Iodine's ability to easily desublimate is utilized to replicate an idealized behavior of water in the atmosphere. Initial results from these experiments are compared to initial numerical models of the same system.

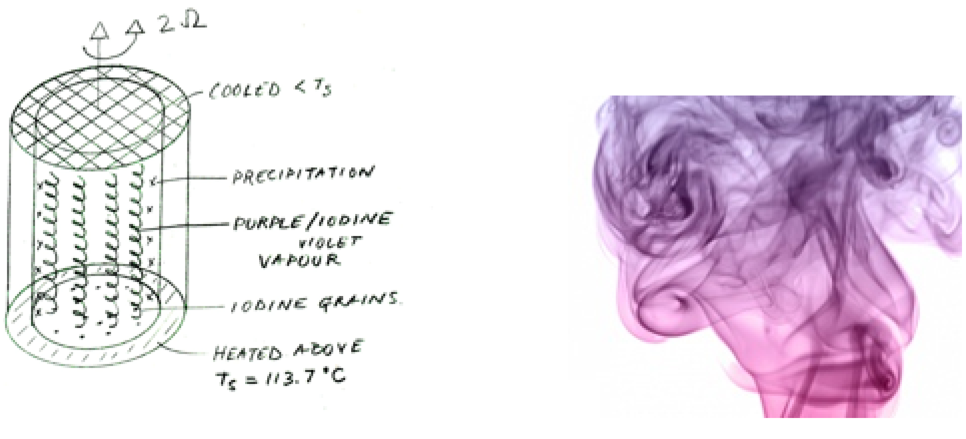

Figure 1: (left)Sketch of experimental set-up for rotating convection with iodine phase change. (right) Sample of iodine vapor.

Berry curvature corrections of geophysical ray tracing equations

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The concept of geometric phase was first introduced by Michael Berry in quantum mechanics to provide a topological interpretation of the Aharonov-Bohm effect [1]. This was later related to the existence of peculiar topological properties in exotic materials such as topological insulators, that are electronic insulators within their bulk but whose edges have quantized conducting states. However these properties are not a specificity of quantum systems, and it was recently proven that topologically-protected edge states also exist in geophysical models such as the shallow water model for equatorial waves [2] or the conservation equations describing acoustic and internal gravity waves in stratified fluids within the Boussinesq approximation [3]. Just like topological insulators, these systems have solutions that are robust to disorder, located at edges of the model and whose number is related to an invariant that depends on the topology of the system's eigenspaces: the first Chern number. This invariant is the integral over phase space of a geometric observable, called the Berry curvature. In condensed matter physics, the Berry curvature modifies the semiclassical equations of motion of electron wave-packets in crystals [4], therefore we will show that this quantity also exists in geophysical models (Figure 1) and yields a correction to the ray tracing equations of corresponding wave-packets.

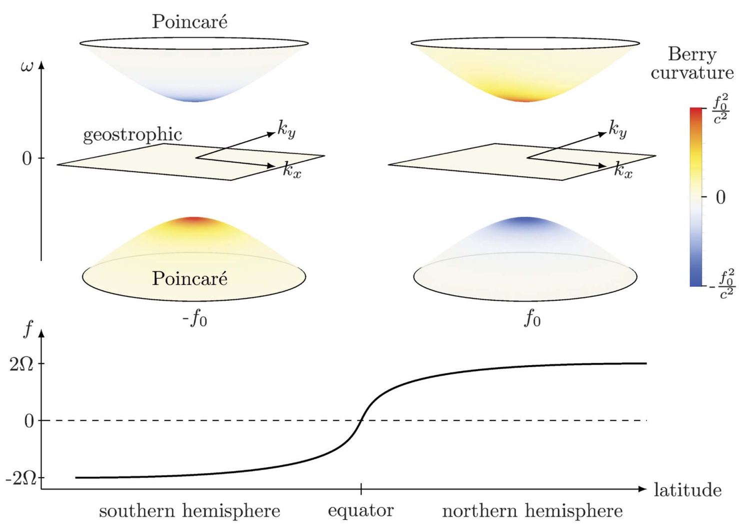

Figure 1: Dispersion relation of the shallow water model in unbounded f-plane geometry for the two signs of the Coriolis parameter f. The color indicates the Berry curvature. [2]

References

[1] Michael Victor Berry. Quantal phase factors accompanying adiabatic changes. *Proc. R. Soc. Lond. A*, 392(1802):45–57, 1984.

[2] Pierre Delplace, JB Marston, and Antoine Venaille. Topological origin of equatorial waves. *Science*, page eaan8819, 2017.

[3] Manolis Perrot, Pierre Delplace, and Antoine Venaille. Topological transition in stratified atmospheres. *arXiv preprint arXiv:1810.03328*, 2018.

[4] Ganesh Sundaram and Qian Niu. Wave-packet dynamics in slowly perturbed crystals: Gradient corrections and berry-phase effects. *Physical Review B*, 59(23):14915, 1999.

Wave propagation and tidal dissipation in giant planets containing regions of layered semi-convection

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Understanding the internal structures of planets and stars, and their effects on the propagation and tidal forcing of internal waves, is an active area of research.

The standard 3-layer model for a giant planet consisting of a rocky/ice core, with a convective envelope of metallic Hydrogen and Helium surrounded by a molecular envelope near the outer edge goes some way in explaining the structure of giant planet interiors. However, recent gravity field measurements from Juno indicate a dilute core of heavy elements that occupies a significant fraction of Jupiter's radius (Wahl et al. 2017). Observations of the satellites of Jupiter and Saturn also indicate higher tidal dissipation rates in these planets than standard theoretical models predict (Lainey et al. 2009, 2012, 2017), which suggests there is an additional mechanism for tidal dissipation. One possible mechanism arises from the presence of heavy element gradients in giant planet interiors, which can lead to regions where ordinary convection is inhibited but double-diffusive convection occurs (also referred to as semi-convection). This can lead to a nearly discontinuous staircase-like density structure, consisting of well-mixed convective layers separated by infinitesimally thin interfaces (semi-convective layers). This staircase structure can strongly modify the propagation of internal waves, and potentially also lead to enhanced tidal dissipation.

I will present calculations to explore how internal wave propagation and tidal dissipation in a giant planet are affected by regions containing semi-convective layers, exploring the dependence of the results on the properties of the staircase. The model adopted here is a Boussinesq system in spherical geometry, which extends previous work in the Cartesian limit by Sutherland (2016) and André et al. (2017). I will first present the dispersion relation for the free modes of a density staircase, which can be compared to that of interfacial and internal gravity waves. I will then show that there is enhanced wave transmission through a staircase when the incident wave is resonant with a free mode of the system. Finally, I will present calculations to study the resulting tidal dissipation and explore its dependence on the properties of the staircase.

On the validity of the frozen-in approximation for acoustic wave propagation through solar granulation

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Solar granulation (small-scale convection near the surface) affects the acoustic modes and is not taken into account in helioseismology. This wave scattering could affect travel time and eigenfrequency measurements and could be a reason for the discrepancy between observed and theoretical eigenfrequencies.

We aim at characterizing the interaction between acoustic waves and turbulent convection. Since the time scales of solar granulation (correlation time about 400 s) and acoustic waves (period about 300 s) are similar, we want to check the validity of the frozen-in medium approximation.

We use finite differences to simulate the propagation of acoustic waves in a 1D medium where the sound speed is treated as a random variable of mean c_0 and standard deviation ϵc_0 in a 30-Mm-wide band. Using Monte-Carlo simulations, we compute the first and second statistical moments of the waves over the realizations of the medium to study the impact of scattering in a statistical sense.

We find that scattering by a random medium generates an attenuation γ_{eff} of the amplitude of the average coherent field of the order of 15 μHz at 3 mHz and a decrease of the effective speed c_{eff} of the medium by 1.5% for a perturbation of strength $\epsilon = 0.1$. For the attenuation, the difference between a granule-like medium and a stationary medium is close to or less than 5% and decreases with increasing frequency. The difference in sound speed is less than 5%. The standard deviation of the wave amplitude however is however more sensitive to the correlation time of the perturbation (difference greater than 100%).

The granule-like and the stationary medium generate effects on the acoustic waves that are of the same order of magnitude. For the impact of scattering on the coherent field, we find the discrepancy small emough for the frozen-in medium approximation to be used, while for the standard deviation, the approximation is not suited. Our results are summarized in Table 1.

Table 1: Relative error for the measured quantities for the granulation-like and supergranulation-like medium.

		Granulation-like	Supergranulation-like
Coherent wave	γ_{eff}	5%	5%
	c_{eff}	-5%	2%
Standard deviation	Amplitude	> 100%	

Propagation of magneto-gravito-inertial waves in rapidly rotating, magnetic stars

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Internal gravity waves provide us with a unique way to probe the interior and dynamics of intermediate-mass and massive stars. Those waves are also able to transport angular momentum that deeply impact their rotational and chemical evolution. However, the propagation, the frequencies of waves and the transport they induce may be strongly affected by rotation (including differential rotation) and the presence of a magnetic field.

For slow rotators, rotation can be taken into account using perturbative methods. For rapid rotators, which is the case of many early-type pulsating stars such as gamma Doradus, delta Scuti, SPB and Be stars, such methods fail, and the eigenmode problem is fully 2D. To investigate the propagation of small-wavelength waves in rapidly rotating, magnetic stars for any amplitude of the stratification, rotation, and magnetic field, we describe them as propagating rays following an Hamiltonian dynamics. This method allows us to efficiently explore the parameter space and identify the different kinds of waves and their properties. I will present results obtained in two cases: non-magnetic, differentially rotating stars and magnetic, uniformly-rotating stars.

Rayleigh-Bénard convection interacting with a melting boundary

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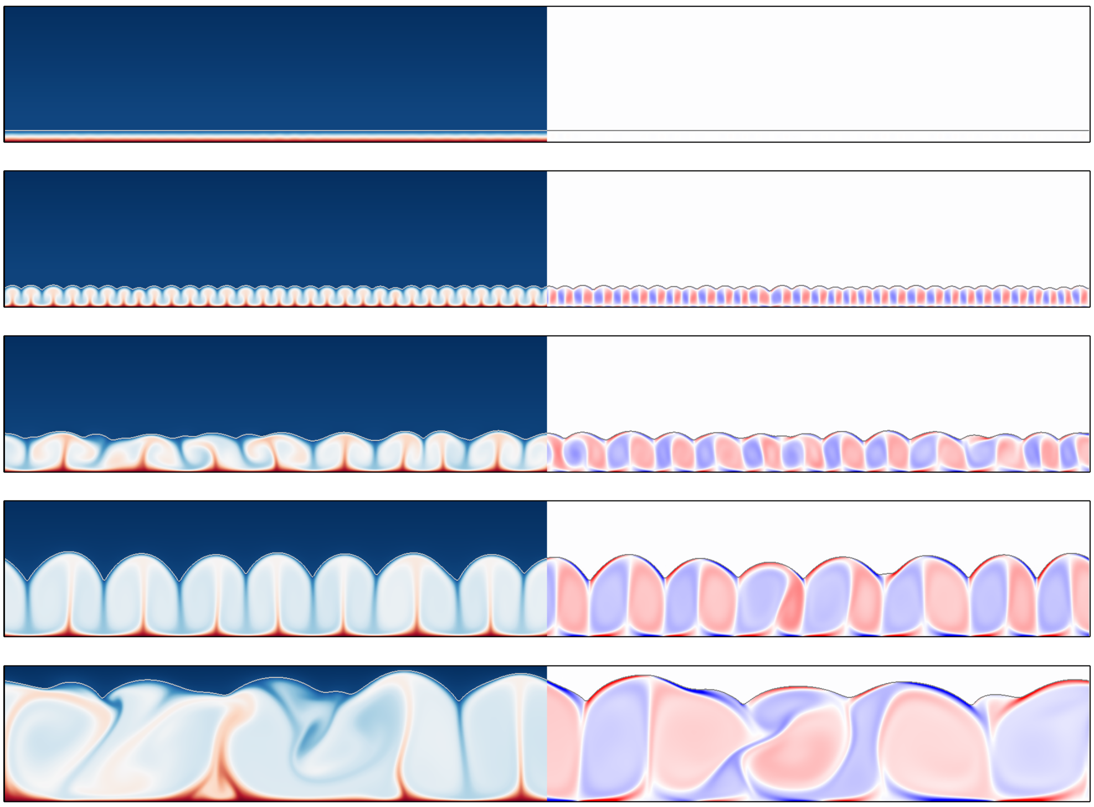
We study the evolution of a melting front between the solid and liquid phases of a pure incompressible material where fluid motion is driven by unstable temperature gradients. In a plane layer geometry, this can be seen as classical Rayleigh-Bénard convection, where the upper solid boundary is allowed to melt due to the heat flux brought by the fluid underneath. This free-boundary problem is studied numerically in two dimensions using a phase-field approach, which we dynamically couple with the Navier–Stokes equations under the Boussinesq approximation. We focus on the case where the solid is initially nearly isothermal, so that the evolution of the topography is related to the inhomogeneous heat flux from thermal convection, and does not depend on the conduction problem in the solid. From a very thin stable layer of fluid, convection cells appear as the depth (and therefore the Rayleigh number) of the layer increases. In the supercritical regime, the continuous melting of the solid leads to dynamical transitions between different convective cell sizes and topography amplitudes. The Nusselt number can be larger than its reference value for a flat upper boundary due to the feedback of the topography on the flow, which can stabilize large-scale laminar convective cells.



Large-scale baroclinic and barotropic instabilities in planetary atmospheres

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Baroclinic and barotropic instabilities are dynamical processes that may occur in stratified fluids in rapid rotation. Baroclinic instabilities draw their kinetic (and potential) energy primarily from the potential energy of the basic state, while barotropic instabilities convert kinetic energy directly from the kinetic energy of the basic state. Linearised theories provide a framework for determining the conditions under which baroclinic, barotropic or mixed instabilities are likely to occur, and also predict the most energetic space and time scales, typically highlighting features of the potential vorticity structure of the basic state as key factors. However, such theories shed little light on how such instabilities are likely to evolve and equilibrate at large amplitude in the presence of forcing and dissipation. For these questions, the nonlinearity of the equilibration must be taken into account, leading either to weakly nonlinear modifications of the linear instability models or heuristic treatments of geostrophic turbulence (e.g. see Pierrehumbert & Swanson 1995; Lovegrove et al. 2002 and references therein).

Based partly on such factors, baroclinic instabilities are widely thought to be the principal means by which the dominant large-scale energy-containing eddies in the Earth's atmosphere and oceans are energized. But what about other planetary atmospheres, which may be in very different dynamical regimes? The Solar System exhibits at least 8 planetary bodies with substantial atmospheres that function under very widely differing parametric and boundary conditions. The atmospheres surrounding the rapidly increasing set of known extra-solar planets further explore regions of dynamical parameter space that have no known analogue within the Solar System. Nonetheless, baroclinic and barotropic instabilities likely play major roles in the majority of these cases.

In this lecture I will briefly review the key theoretical results determining when baroclinic or barotropic instabilities can occur, before going on to examine ways in which such instabilities might equilibrate under conditions relevant to both terrestrial and gas giant planets. Simulations using highly simplified numerical models and even laboratory experiments reveal clear trends in fully developed flow behaviour, from barotropically unstable circumpolar waves to parallel trains of baroclinic waves and turbulence as the strength of planetary rotation is increased. The impact on planetary heat transfer and super-rotation will also be considered, highlighting conditions where super- or sub-rotation and/or baroclinic adjustment may occur. We will conclude by examining to what extent such simple numerical models capture the observed features in Solar System atmospheres.

References

Lovegrove, A. F., Moroz, I. M. & Read, P. L. 2002. Bifurcations and instabilities in rotating, two-layer fluids: II. β-plane. *Nonlin. Proc. Geophys.* **9**: 289–309.

Pierrehumbert, R. T. & Swanson, K. L. 1995. Baroclinic instability. *Annu. Rev. Fluid Mech.*, **27**: 419–467.

Vortices in self-gravitating Protoplanetary disks

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Large scale vortices due to hydrodynamical instabilities, as for instance the Rossby Wave Instability or Baroclinic instability, are thought to play a significant role in the evolution of protoplanetary disks and the formation of the planetesimals. Their presence in the outer regions of circumstellar disks is possibly betrayed by recent observations with ALMA and VLT.

We performed 2D hydrodynamical simulations of vortex evolution in a disk in which self-gravity is taken into account. First, we show that quasi-steady vortices can survive for a large number of rotation periods and migrate very slowly in the disk. Then, we present the results of two-phase numerical simulations in which the solid particles embedded in the gas are described as a second pressureless fluid. We find again that dust particles are trapped in the vortex whereas big boulders tend to decouple from the gas and liberate in the horseshoe region associated to the vortex. We will present the difficulties encountered in the study of the dust/gas mixture in the core of the vortex and will speculate on the evolution of the swarm of librating boulders.

Differentially heated rotating annulus experiments to study gravity wave emission from jets and fronts

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Significant internal gravity wave (IGW) activity has been frequently observed in the vicinity of jet/front systems in the atmosphere. Although many studies have established the importance of these non-orographic sources, the mechanisms responsible for spontaneous wave emissions is still not fully understood. The complexity of the three-dimensional flow pattern and distribution of the sources over large areas point towards the need of laboratory experiments and idealised numerical simulations to help with the correct interpretation of the fundamental dynamical processes in a simplified, but yet realistic flow. In this study, we emphasise that the differentially heated rotating annulus experiment, classically showing an aspect ratio of about one, is not a particularly favourable set-up to investigate atmosphere-like emission of gravity waves from baroclinic jets due to an unrealistic ratio between the buoyancy frequency N and the Coriolis parameter f. The latter is much larger than one for the atmosphere but smaller than one for the classical annulus. Hence, we present an overview of modified versions of the classic baroclinic experiment, with a more realistic N/f, as a better choice for the study of IGWs. The first modified experiment is a thermohaline version in which a juxtaposition of convective and motionless stratified layers can be created by introducing a vertical salt stratification. This new experimental setup, coined "barostrat instability", allows studying the exchange of momentum and energy between the layers, especially by the propagation of IGWs. Moreover, in contrast to the classical tank without salt stratification, we have layers with $N/f > 1$. A ratio larger than unity implies that the IGW propagation in the experiment is expected to be qualitatively similar to the atmospheric case. Interestingly, we found local IGW packets along the jets in the surface and bottom layers where the local Rossby number is larger than 1, suggesting spontaneous imbalance as generating mechanism [1], and not boundary layer instability. The second experiment is a newly built rotating annulus, supported by numerical simulations [2]. This one is much wider with a small fluid depth compared to the classical set-up and has a larger temperature difference between the inner and outer cylinder walls, which is more atmosphere-like since it shows an $N/f > 1$ even without the vertical salt stratification. The conditions for gravity wave emission in this new configuration are examined in detail. Moreover, we compare numerical simulations and experimental data focusing on the variations of the temperature T and N. It becomes clear that despite the fact that the global structure and baroclinic instability characteristics are very similar, model and experiment show deviations in N with implications for gravity wave emission. Nevertheless, the complex horizontal structure of N with largest values along the baroclinic jet axis lend credence to the experimentally observed trapped inertia-gravity waves [1].

References

[1] C. Rodda, I. Borcia, P. Le Gal, M. Vincze and U. Harlander, "Baroclinic, Kelvin and inertia-gravity waves in the barostrat instability experiment," Geophysical and Astrophysical Fluid Dynamics, pages 1-32, 2018,

[2] S. Hien, J. Rolland, S. Borchert, L. Schoon, C. Zlicke, and U. Achatz, "Spontaneous gravity wave emission in the differentially heated rotating annulus experiment," J. Fluid Mech., 838:5–41, 2018.

Inertia-gravity-wave scattering by quasigeostrophic turbulence

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Oceanic internal tides and other inertia–gravity waves propagate in a turbulent flow whose lengthscales are similar to the wavelengths. Advection and refraction by this flow cause scattering of the waves, redistributing their energy in wavevector space. As a result, initially plane waves radiated from a source such as a topographic ridge become spatially incoherent away from the source, and in the presence of vertically sheared flow the lengthscales of the waves may change. Modelling the quasigeostrophic flow by a random field, this process can be described statistically using a kinetic equation satisfied by a wavevector–resolving wave–energy density. We present a brief derivation of this equation and its use in quantifying aspects of the scattering process, theoretically and numerically, and discuss these in relation to the simpler case of an isotropic and barotropic flow. Recent work has been to consider a horizontally isotropic flow, where we can compare predictions from and simulations of the kinetic equation against simulations of the three-dimensional Boussinesq equations in initial-value and forced scenarios. (Joint work with Jacques Vanneste and Hossein Kafiabad.)

Stability of nonlinear atmospheric gravity waves

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The majority of gravity waves in the atmosphere are excited in the lowest 10 km where the waves are effectively described by linear theory since their amplitudes are small. They grow in amplitude as they propagate upwards due to the decreasing background density. Some of the waves reach far into the "deep" atmosphere where their amplitudes cannot be considered small anymore. Here, nonlinear wave theory governs the dynamics.

The governing equations for my theoretical analysis are modulation equations that result from nonlinear Wentzel-Kramers-Brillouin asymptotics of the Navier-Stokes equations. They exhibit stationary solutions modeling mountain lee waves as well as traveling wave solutions like locally confined wave packets. The latter possess counterintuitive properties that are neither available in linear nor weakly nonlinear theory. For instance, the group velocity, as defined usually by the derivative of the dispersion relation, may not coincide with the wave's actual envelope velocity. I am in particular concerned with the stability the solutions as those are relevant for applications such as subgrid-scale parametrisations in weather and climate models. For this endeavor I exploit novel methods of functional and numerical analysis in the framework of atmospheric physics.

An analytical example of the inertial/strong-field scaling regimes for the saturation of the dynamo instability

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I will present analytical examples of fluid dynamos that saturate through the action of the Coriolis and inertial terms of the Navier-Stokes equation. The flow is driven by a body force and is subject to global rotation and uniform sweeping velocity. The model can be studied down to arbitrarily low viscosity and naturally leads to the strong-field scaling regime for the magnetic energy produced above threshold: the magnetic energy is proportional to the global rotation rate and independent of kinematic viscosity. In the absence of global rotation, the system displays a visocity-independent inertial scaling regime reminiscent of experimental dynamos. Because the model is based on scale-separation only, it can be studied at arbitrary distance from the dynamo threshold. Far from the threshold, we obtain an asymptotic regime where the magnetic energy is independent of both kinematic viscosity and magnetic diffusivity. Without global rotation, this regime corresponds to the equipartition of kinetic and magnetic energy. With global rotation, the ratio of kinetic to magnetic energy is propotional to the Rossby number.

The Formation of Double-Diffusive Layers in a Weakly-Turbulent Environment

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Double diffusion is a type of convective mixing process that may arise in the oceans where temperature and salinity determine density gradients. Active double-diffusive convection manifests as stacked well-mixed water layers, forming a staircase structure. The Arctic Ocean exhibits a prominent double-diffusive staircase which indicates how deep-ocean heat is mixed upward toward the sea ice. In this study, we employ a one-dimensional numerical model to examine how this double-diffusive heat transport may be influenced by mechanical mixing, or turbulence, such as that driven by winds and waves. Model results indicate that above a threshold level of turbulence, double-diffusive convection can no longer operate to generate a well-formed staircase. This threshold is framed in terms of a critical diffusivity ratio (ratio of effective salinity diffusivity to effective thermal diffusivity) that cannot be exceeded for a staircase to persist. This critical ratio is not a universal constant, but rather differs for each staircase. Results further suggest that increased levels of shear-driven turbulence lead to decreased heat fluxes; if a staircase is subject to intermittent turbulence levels (below the critical level), vertical heat fluxes will be smaller than in the absence of shear-driven turbulence. Both microstructure and acoustic measurements of the Arctic Ocean staircase are analyzed to explore model results in context with observations. Results contribute to understanding how turbulence affects vertical heat transport in a changing Arctic Ocean that may experience higher wind-driven mixing as sea-ice continues to retreat.

Internal wave focusing by a horizontally oscillating torus: nonlinear aspects

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Dissipation due to nonlinear breaking of internal tides is believed to play an important role in the mixing of the abyssal ocean, and therefore in the large-scale ocean circulation.

In the laboratory, we generate the internal waves by an oscillating objects in a linearly stratified fluid. Over the past five decades the dynamics of particularly diverging internal waves have been considered, such as generated by cylinder (Mowbray & Rarity, 1967) or spheroid (Ermanyuk et al., 2011; Shmakova et al. 2017). However, the localized zones representing hot spots for incipient overturning may occur close to curved topographies owing to the concentration of energy due to wave focusing (Buijsman et al. 2014, Peliz et al. 2009). Ermanyuk et al. (2017) showed experimentally with a horizontally oscillating torus that in a linear regime the wave amplitude amplifies in the focal zone and increases linearly with increasing oscillation amplitude.

Here we investigate weakly nonlinear and nonlinear effects of focusing internal waves generated by a torus with radius b and a circular cross-section of radius a oscillating horizontally with amplitude A. LIF and PIV techniques are used to measure the isopycnal displacement and the velocity, respectively. The nonlinear effects are investigated in terms of wave slopes as a function of newly developed focusing number defined as $Fo = (A/a)\epsilon^{-1/2}f(\theta)$, which includes the amplitude increase due to focusing as $\epsilon^{1/2} = \sqrt{b/a}$ and the variation in energy with the propagation angle θ. The data obtained for different sizes tori predict the wave breaking for the critical value of $Fo \approx 0.23$. Below this value, nonlinear effects in the focal zone arise in the generation of the vertical mean flow and evanescent higher harmonics. Above the critical number the focal region is unstable due to triadic wave resonance (TRI) that is formed of the fundamental wave and two subharmonic waves generated in the focal zone. The observed TRI in three dimensional flow resembles closely the resonance obtained by Bourget et al. (2013) for a two-dimensional flow due to the symmetry of our problem, and thus with the amplitude maximum in the symmetry plane (Shmakova et al., 2019).

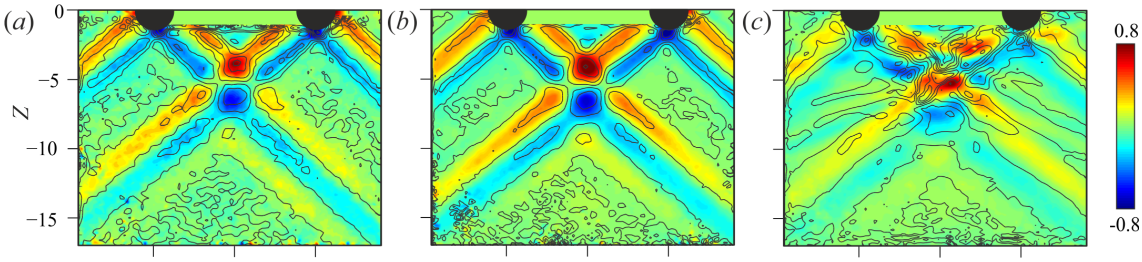

Figure 1: Instantaneous profiles of the normalized horizontal longitudinal velocity $u/(A\omega)$ (color) and contours of the horizontal transverse vorticity at rightmost torus position in the steady regime after 20 oscillation periods with (a) $Fo = 0.053$ (linear regime), (b) $Fo = 0.16$ (weakly nonlinear regime) and (c) $Fo = 0.33$ (nonlinear regime).

The inertial wave activity during spin-down in a rapidly rotating penny shaped cylinder

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Previously, Oruba, Soward & Dormy (J. Fluid Mech., vol. 818, 2017, pp. 205–240) considered the primary quasi-steady geostrophic (QG) motion of a constant density fluid (viscosity ν) that occurs during spin-down in a cylindrical container, radius L, height H, rotating rapidly (angular velocity Ω) about its axis of symmetry subject to mixed rigid and stress-free boundary conditions for the case $L = H$. Now, Direct Numerical Simulation (DNS) at large $L = 10H$ and small Ekman number $E = \nu/H^2\Omega = 10^{-3}$ reveal significant inertial wave activity on the spin-down time-scale. Our analytic study, based on $E \ll 1$, builds on the results of Greenspan & Howard (J. Fluid Mech., vol. 17, 1963, pp. 385–404) for an infinite plane layer $L \to \infty$. At large but finite L, the meridional (QG-)flow, that causes the QG-spin down, is blocked by the distant lateral boundary so providing a QG-trigger for inertial waves. The situation is complicated in the unbounded layer by secondary maximum frequency (MF) inertial waves (a manifestation of the transient Ekman layer). Their blocking provides a secondary MF-trigger for more inertial waves. We solve initial value problems for both triggers by Laplace transform methods. The ensuing complicated inertial wave structure is explained analytically on approximating our cylindrical geometry at large radius r by rectangular Cartesian geometry, valid for $L - r = O(H)$ ($L \gg H$). Other than identifying small scale structure near $r = L$, our main finding is that inertial waves radiated away from the outer boundary (but propagating towards it) reach a distance determined by the group velocity. Agreement with the DNS is good.

Internal gravity waves in the ocean and the atmosphere

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Internal gravity waves are ubiquitous in the ocean and the atmosphere. Despite their small-amplitude, minute-to-hour time scale and vertical wavelengths from about one meter to about one kilometer, oceanic internal gravity waves play an essential role in the meridional overturning circulation. This circulation results from the sinking of the deep-water masses at a few locations in the winter hemispheres, which go back to the surface by mixing with the surrounding fluid. This circulation is at the Earth scale and has a time scale of one thousand years. Internal gravity wave breaking has been conjectured and recently convincingly shown to be the main mixing process of the deep-water cold masses. The first lecture is devoted to this story: we will show from field measurements that the ocean is in a turbulent state, that internal gravity wave breaking is the main contributor to mixing and discuss about the generation and breaking processes of these waves.

The second lecture deals with internal gravity waves in the atmosphere. There, the interaction with wind is essential in wave transformation (while interaction with currents may play a marginal role in fluid mixing in the ocean). This is reflected in the well-known concept of critical level where internal gravity waves can deposit the momentum they transport and accelerate or decelerate the wind. As for the ocean lecture, we will review the main generation processes of internal gravity waves in the atmosphere. We will illustrate the importance of critical level via the quasi-biennal oscillation, a reversal of the wind in the stratosphere every two years or so.

The third lecture will focus on lee waves in the atmosphere. Lee waves are generated by the blowing of the wind over a mountain range in a stratified air. We will make a journey through the life of lee waves. We will derive the wave solution in the linear regime for an idealized sinusoidal mountain and next for an arbitrary-shape isolated mountain and describe nonlinear situations where strong winds along the slope of the mountain are induced by lee wave breaking in altitude and vortical structures called rotors form close to the ground, which can be a hazard for airplanes.

The fourth lecture will go back to the ocean. It will be devoted to on-going work on the interaction of a current with an idealized topography from joint numerical and laboratory experiments. While most studies on this topic have been done in two dimensions, we consider the more realistic case of a three-dimensional topography. Such a topography behaves indeed very differently from a two-dimensional one, because the fluid can flow horizontally around the topography as well as rise above it, thus possibly generating a vortical wake behind the topography and a lee wave above it. The objective of this work is to estimate the relative contribution of the turbulent wave and lee wave breaking on fluid mixing, namely, from an oceanic view point, on the relative amounts of local and interior mixing, depending on the flow parameters.

Figure 1: View of noctilucent clouds from Kustavi, Finland (61N, 21E) on 22 July 1989 showing characteristic bands and streak structures. In this case, bands are separated by about 50 km and streaks by about 3 to 5 km (from Fritts et al. 1993; photograph by Pakka Parviainen).

An Introduction to Dynamos

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The generation of magnetic field in an electrically conducting fluid generally involves the complicated nonlinear interaction of flow turbulence, rotation and field. This *dynamo* process is of great importance in geophysics, planetary science and astrophysics, since magnetic fields are known to play a key role in the dynamics of these systems. In this talk I shall give an introduction to dynamo theory, laying the groundwork, introducing the equations and techniques that are at the heart of dynamo theory, before presenting some simple dynamo solutions. The problems currently exercising dynamo theorists are then introduced, along with the attempts to make progress. The talk concludes with the argument that progress in dynamo theory will be made in the future by utilising and advancing some of the current breakthroughs in neutral fluid turbulence such as those in transition, self-sustaining processes, turbulence/mean-flow interaction, statistical methods and maintenance and loss of balance.

Interplay between tides and convection in global models

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Tidal interactions determine the orbital and spin evolution of celestial fluid bodies when they are sufficiently close to one another. A weakness of the tidal theory is to deal with additional flows on which the tides are superimposed, notably convection. Indeed, the latter is often filtered out in tidal studies. Hence, elucidating the interplay between tides and convection is worthy of interest, e.g. for giant planets or low-mass (convective) stars. Turbulent convection is believed to provide a turbulent damping of the large-scale tidal flow, i.e. the equilibrium tide [1]. The effective turbulent viscosity ν_{t} ought to be reduced, e.g. when the orbital angular frequency Ω_{orb} is large compared to the characteristic frequency of the convective motions Ω_{cv} (neglecting the fluid rotation). However, the phenomenological prescriptions of this reduction are debated [1, 2]. We conduct nonlinear simulations of Boussinesq convection in the presence of tides in global geometries, by using the code NEK5000. Our preliminary results (figure 1) suggest that the reduction factor should scale as $\propto \Omega_{\mathrm{orb}}^{-2}$ in non-rotating flows, in agreement with local simulations [3, 4]. Additional physical ingredients will be then included, e.g. rotation. Indeed, the equilibrium tide can sustain the elliptical instability in rotating flows [5], even against the turbulent damping of convection in planetary interiors [6, 7]. However, the influence of strong density variations remains elusive. By combining local and global linear stability methods in ellipsoids, we confirm that the maximum growth rate of the elliptical instability is largely unaffected in well-mixed (isentropic) interiors. Thus, the elliptical instability is not a priori inhibited in convective (planetary) interiors.

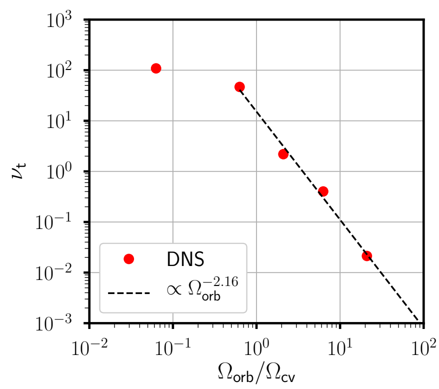

Figure 1: Turbulent viscosity ν_{t} acting on the equilibrium tide, as a function of the orbital angular frequency Ω_{orb} of the tides normalised by the convective angular frequency $\Omega_{\mathrm{cv}} \propto Ra^{1/2}$, where Ra is the Rayleigh number.

References

[1] Zahn J.-P., 1966, 29, 313
[2] Goodman, J. & Oh, S. P., 1997, The Astrophysical Journal, 486(1), 403
[3] Ogilvie, G. I. & Lesur, G., 2012, MNRAS, 422(3), 1975-1987
[4] Duguid, C. *et al.*, 2019 (in prep.)
[5] Kerswell R. R., 2002, Annual Review of Fluid Mechanics, 34, 83
[6] Cébron D. *et al.*, 2010, Geophysical Journal International, 182, 1311
[7] Clausen N. & Tilgner A., 2014, Astronomy & Astrophysics, 562, A25

Nonlinear tides in radiative stellar interiors

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Surface magnetic fields have been detected in 5% to 10% of isolated hot stars, which are mainly stably stratified in density (i.e. radiative). These fields are often thought to have a fossil origin [2], i.e. inherited from the stellar formation phase. However, magnetic hot stars are much scarcer (around 1.5 %) in close binaries [1], which challenges the fossil theory. This may be due to the elliptical (tidal) instability [3, 4], but its outcome in radiative interiors is poorly understood [5]. Here, the elliptical instability is investigated in stratified interiors, modelled as rapidly rotating, stably stratified Boussinesq fluid ellipsoids (equatorial distortion β_0). First, a comprehensive (global and local) theory of the instability at the linear onset will be outlined. It turns out that the elliptical instability is generated by triadic resonances involving mixed inertia-gravity waves in short-period, hot binaries. Second, a mixing-length theory of the turbulent mixing, supported by proof-of-concept nonlinear simulations [6], will be presented. Two regimes of tidally driven, rotating stratified turbulence are identified as a function of N_0/Ω_s (figure 1), where N_0 is the strength of the stratification and Ω_s the spin angular velocity of the fluid. In the strongly stratified regime ($N_0/\Omega_s \gg 1$), relevant for stellar stratified interiors, the typical turbulent magnetic diffusion evolves as $\sigma_\eta \propto \beta_0^2\,\Omega_s$ (fig. 1b). Hence, the turbulent decay of fossil magnetic fields would occur in less than 10^6 years for typical close hot binaries (with $\beta_0 \in [10^{-3}, 10^{-2}]$). This new physical scenario appears to be compatible with the observed dearth of close magnetic binaries [6].

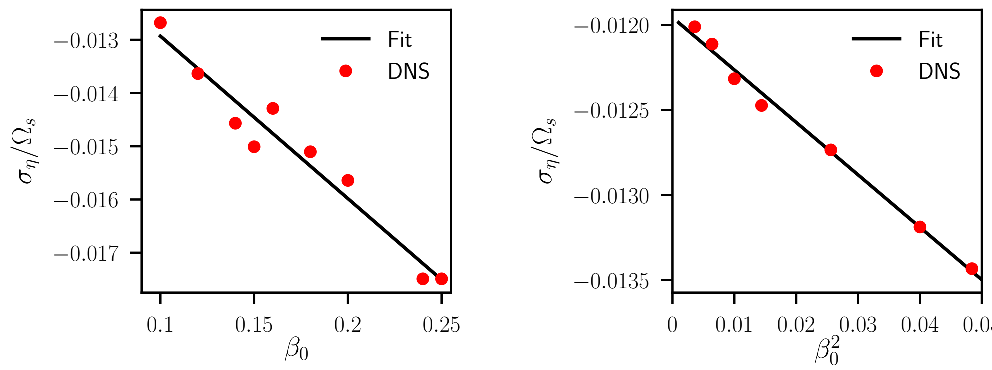

Figure 1: Mixing of fossil fields by nonlinear tides. Dimensionless turbulent decay rate $\sigma_\eta/\Omega_s \leq 0$ as a function of the ellipticity β_0. (a, left) Weakly stratified regime ($N_0/\Omega_s \simeq 0$). (b, right) Strongly stratified regime ($N_0/\Omega_s = 10$).

References

[1] Alecian E. *et al.*, 2017, arXiv preprint arXiv:1705.10650

[2] Braithwaite J., & Spruit H. C., 2017, Royal Society Open Science, 4, 160271

[3] Kerswell R. R., 2002, Annual Review of Fluid Mechanics, 34, 83

[4] Le Bars M. *et al.* 2010, Physics of the Earth and Planetary Interiors, 178, 48

[5] Vidal J. *et al.*, 2018, Mon. Not. Roy. Astron. Soc, 475, 4579

[6] Vidal J. *et al.*, 2019 (in prep. for Mon. Not. Roy. Astron. Soc)

WKBJ Theory of Triad Interactions of Internal Gravity Waves in Varying Background Flows

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Internal gravity waves are a well known mechanism of energy transport in stratified fluids such as the atmosphere and the ocean. Their abundance and importance for various geophysical processes like ocean mixing and momentum deposition in atmospheric jets are widely accepted. While resonant wave-wave interactions of monochromatic disturbances have received intensive study, little work has been done on resonant interactions between wave trains that are modulated by a variable mean flow to leading order.

We present a Boussinesq WKBJ theory for interacting small amplitude gravity wave trains propagating through a finite amplitude background flow. In such a scenario the local wave numbers and frequencies depend on the variation of the background and are not constant. As a result, the wave trains are allowed to pass through resonance conditions and exchange energy in a small neighborhood around resonance. Our analysis is based on the method of multiple scales and the weak asymptotic theory.

To test the theory we use idealized simulations in which two wave trains generate a third by passing through resonance in a sinusoidal background shear flow. Comparing a corresponding WKBJ ray tracer with wave resolving large eddy simulations we find good agreement. Furthermore we assess the impact of the amplitude of the background flow on the energy exchange between the interacting wave triad.

Intermittent planet migration and the formation of multiple dust rings in protoplanetary disks

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Over the last few years, multi-wavelength observations have underlined that the gas and dust of protoplanetary disks may have very different spatial distributions, more especially for the large dust particles (dust with a size of order a millimetre and beyond). These distributions are very diverse (spiral waves, annular gaps, horseshoe-shaped asymmetries) and can be interpreted as signatures of the presence of (hidden) planets. These observations stress the need for a better understanding of how disk-planet interactions generally, and planetary migration more specifically, impact the dust's thermal emission in protoplanetary disks.

The gravitational interaction between planets and the protoplanetary disk gas changes rapidly the distance between the planets and the star. This is known as planetary migration. Many studies have examined how the direction and speed of planetary migration depend on the planet's mass and the physical properties of the disk gas, with the aim to explain the orbital properties of exoplanets. Dust is most often discarded in this kind of studies because its mass content is much smaller than that of the gas and it should therefore have a negligible impact on planetary migration. Usually, the presence of N dark rings in the dust thermal emission of protoplanetary disks is interpreted as the presence of N fixed planets which would each create an accumulation of dust near the local maximum in the disk gas pressure (cf observation in Fig. 1, left). The aim is here to investigate the dynamics and the thermal emission of dust in a protoplanetary disk where one single planet migrates intermittently, with fast stages of inward migration and stages where the planet stalls, which leads to the formation of multiple dust rings (cf simulation in Fig. 1, right).

We perform hydrodynamical simulations modeling both the gas and dust of a protoplanetary disk where one Saturn mass planet is formed. We are using the public hydrodynamical code FARGO. These simulations allow us to predict the spatial distribution of dust from a few microns to a few centimetres in size, by varying the physical properties of the disk. Then we use the results of simulations to compute synthetic images of the dust's continuum emission as it would be observed in the radio by interferometric imaging, with ALMA or NOEMA for example. For this purpose we use the public radiative transfer code RADMC-3D.

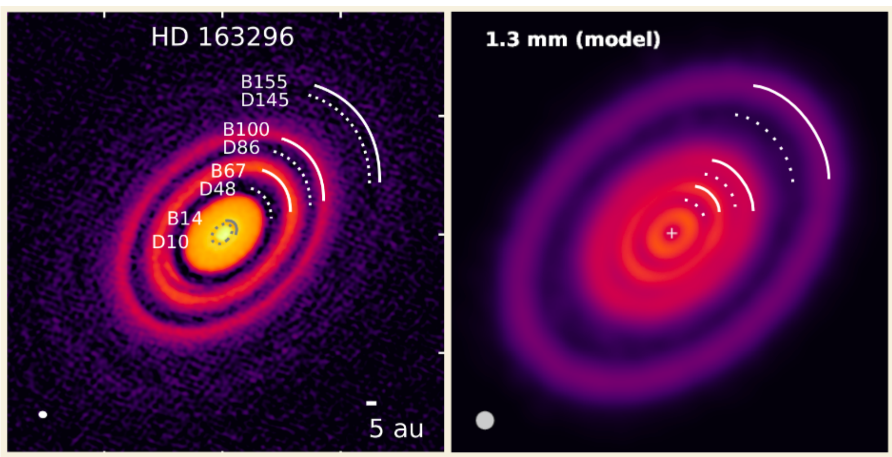

Figure 1: HD 163296 from DSHARP (Huang et. al (2019)) and FARGO+RADMC-3D model

Nonlinear dynamics of forced baroclinic critical layers

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Critical levels are singularities of linear steady waves in inviscid shear flows. When they are generated by a steady forcing, the linear evolution of critical layers is characterized by secular growth of disturbance amplitude and decreasing width, while the outer flow remain steady (Stewarston 1978, *Geophys. Astrophys. Fluid Dyn.* 9, 185-200). Classical critical levels are where the basic flow velocity matches the phase velocity of waves $U = c$. In this paper, we study the forced 'baroclinic critical levels' which arise in stratified fluids with horizontal shear at $c - U = \pm N/k$, based on the buoyancy frequency N and the horizontal wavenumber k. Linear theory predicts the baroclinic critical layer has very similar behaviours to the classical critical layer of Stewarston (1978), characterized by secular growth and decreasing width. The critical layer must therefore become nonlinear. By developing a nonlinear baroclinic critical layer theory, we show that the baroclinic critical level has a wave-selecting property which filters out harmonics. By contrast, mean-flow vorticity becomes significantly strong and forms a pattern of dipolar stripes. At later times, the vorticity begins to grow exponentially over yet a much smaller regions whose width decreases exponentially. This exponential blowup suggests a new stage of more complicated evolution.

Magneto-buoyancy in the solar tachocline

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Magneto-buoyancy is a crucial ingredient of the solar dynamo cycle, but operates in a parameter regime that is extremely difficult to reproduce in numerical simulations. Moreover, the mathematical approximations commonly employed in models of stellar fluid dynamics (anelastic, Boussinesq, etc.) produce inconsistent results in the relevant parameter regime. This talk will investigate the range of applicability of these approximations, and seek to identify the characteristic length- and time-scales of magneto-buoyancy in the tachocline.

Zonal flow-induced gravity anomalies - what have we learned from Juno and Cassini?

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Recently, the spacecrafts, Juno and Cassini, orbited Jupiter and Saturn while gathering detailed data of the gravity potential characterized by a set of gravity moments, J_n (see fig. 1). Deep reaching zonal winds induce perturbations in the pressure and consequently also in the density field yielding a characteristic modulation of the gravity signal.
The odd moments $(2n+1)$ directly contain the signal of the antisymmetric component of the deep zonal flow while the even ones $(2n)$ are to a large extent obscured by the solid body rotation. Nevertheless, should the winds be deeply penetrating structures, this would inevitably lead to a strong deviation from the solid body model for high order even n (fig. 1). Hence the measurements were used to infer the depth at which the winds are damped - supposedly by electromagnetic forces - and yield an estimate of where the top of the dynamo region is located. Results should help to end the longstanding dispute concerning whether the zonal flows are merely surface phenomena or are deep-rooted, cylindrical structures.
Within this study, we revisit the major simplifications typically made in order to select the appropriate depth decay profile of the zonal flows which appears most compatible with the observed gravity anomaly. This concerns in particular a thorough sensitivity analysis regarding the chosen density and gravity profile, as well as modifications of the radial decay functions. As the critical variable is in fact the density flux multiplied by an n dependent radial factor $(r^{n+2}\partial_r(\rho U))$, there is a strong radial variation of the susceptibility for different n. In the published results of Juno, the best fitting radial profile is a rather linear radial decay. However, this seems somewhat incompatible with the commonly made assumption that the zonal flows are terminated by electric currents which increase abruptly at the edge of the dynamo region. We also shed light on the heavily debated simplification to take only density anomalies into account and ignore the fact that the gravity is also being perturbed. Therefore we have developed, and successfully tested, a numerical approach which allows us to bridge the gap between the easily solvable thermal wind equation and the more complex, yet more mathematically rigorous thermal-gravitational wind equation.

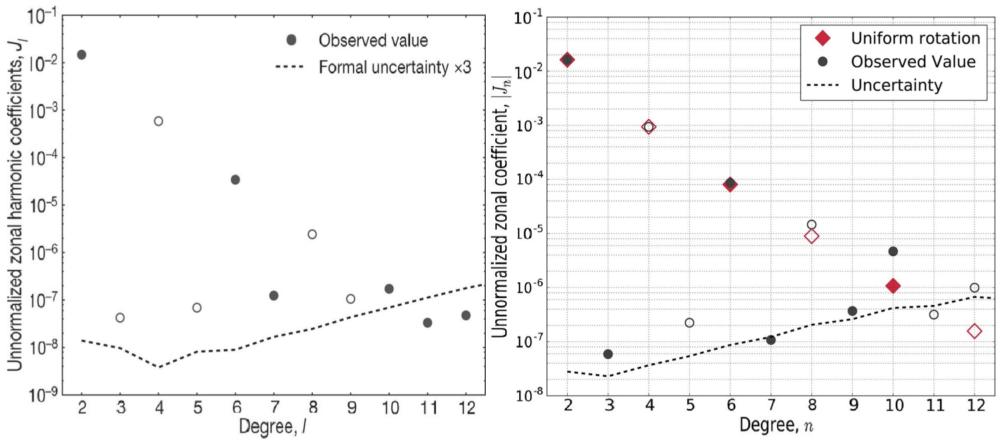

Figure 1: Observed gravity moments J_n for Jupiter (left, Iess et al. Nature 2018) and Saturn (right, Iess et al., Science 2019). Filled symbols indicate positive, open symbols negative values.

Mean flow generation in rotating annulus with stochastic methods

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In fluid mechanics, the notation "energy cascade" refers to that the energy transfers from large scale motion to small scale motion, which is also called direct energy cascade. An inverse energy cascade also exists, where the energy transfers upscale from small scale motion to large scale motion. In a 3D rotating flow field, the entire turbulent fields can be described as a composition of interacting inertial waves. Linear inertial waves transfer injected energy and distribute the energy directly and inversely both in space and time. This theory is experimentally studied in Yarom and Sharon (2014).
Our research project focuses on investigating the influence of deep-seated stochastic shear force on Taylor-Couette flow. The laboratory experiments were carried out with an annulus that consisted of two independent rotating cylinders and partially filled with deionized water. A conic hollow cylinder is fixed at the bottom with small obstacles to generate stochastic motions and rotates simultaneously with the outer cylinder. The schematic sketch is shown in Figure 1. A camera is installed over the tank and co-rotating with the outer cylinder. Illuminated by a co-rotating horizontal laser sheet, the flow velocity field in horizontal section can be quantitatively measured by using Particle Image Velocimetry (PIV).
Our investigation experimentally studies the influence of a stochastically forced motion on the rotating flow. With stochastic forcing, the obstacles on the bottom excite small scale inertial waves. These waves transfer energy to wide range of length- and timescales and therefore might lead to a deep seated steady turbulent rotating flow and constraint large-scale motions.

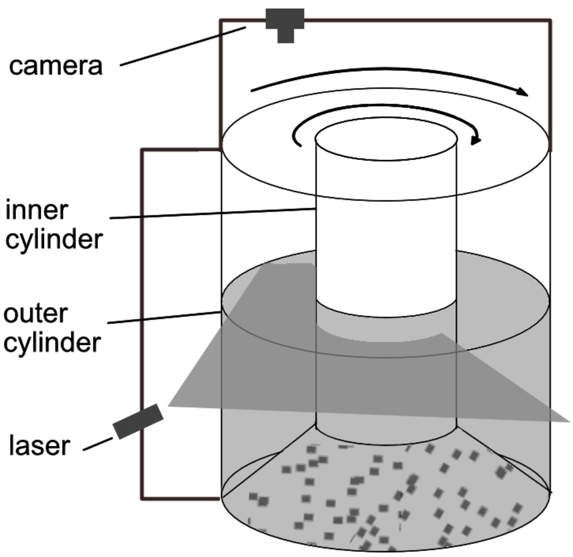

Figure 1: Schematic sketch of the experiment configuration. Radius of the inner/outer cylinder is 7.5/20 cm, tank height is 50 cm.

Reference

Yarom, E., Sharon, E. (2014). Experimental observation of steady inertial wave turbulence in deep rotating flows. Nature Physics, 10(7), 510-514.

Linear and nonlinear waves and instabilities coupled to moist convection in tropics

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Rotating shallow water model is a classical tool in tropical meteorology. I will show how to include, in a simple albeit self-consistent way [1], the thermodynamics of the moist air in the model. Thus obtained model allows for analytic and low-cost computational approaches to the understanding of the influence of moist convection onto large-scale atmospheric dynamics, of obvious importance in weather and climate studies. I will then demonstrate that the effects of moist convection substantially modify the properties of linear and nonlinear [1], [2] equatorial waves and their interactions with the oceanic warm-pool and topography, and lead to specific condensation and precipitation patterns. I will also show how instabilities of jets [3] and hurricane-type vortices [4], [5] are modified in the presence of moist-convection.

References

[1] V. Zeitlin, "Geophysical Fluid Dynamics: understanding (almost) everything with rotating shallow water models", 489 pp, Oxford University Press, 2018.

[2] M. Rostami and V. Zeitlin, "Eastward-moving convectively-enhanced modons in the equatorial tangent plane", Phys. Fluids, *to appear*, 2019.

[3] J. Lambaerts, G. Lapeyre and V. Zeitlin, "Moist vs dery baroclinic instability in a simplified two-layer atmospheric model with condensation and latent heat release", J. Atmos. Sci., **69**, 1405-26, 2012.

[4] N. Lahaye and V. Zeitlin, "Understanding the instabilities of tropical cyclones and their evolution with a moist-convective rotating shallow water model", J. Atmos. Sci., **73**, 505-23, 2016.

[5] M. Rostami and V. Zeitlin, "An improved moist-convective rotating shallow-water model and its application to instabilities of hurricane-like vortices", Q. J. Royal Met. Soc., **144**, 1450-62, 2018.

A united asymptotic approach to fluid dynamical problems in rapidly rotating systems

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Here are primarily three special characteristics in rapidly rotating fluids: an overwhelming constraint on fluid motions imposed by controlling rotational forces; unique types of oscillatory motions, inertial oscillations and inertial waves, solely caused by the action of rotational forces; and a viscous boundary layer, produced by the effect of fast rotation, that differs markedly from that in non-rotating configurations. These three characteristics underlie the foundation of the asymptotic theory of rapidly rotating fluids. Since a relatively simple mathematical solution describing inertial oscillatory or wave motions can be readily obtained at leading-order proximation, theoretical progress on the corresponding viscous problems, such as convection and precession, can be usually made via the application of an asymptotic or perturbation methods. We shall discuss an united asymptotic theory for convective instabilities and precessional flows in rapidly rotating, self-gravitating fluid spheres, including the simplest asymptotic solution of convection-driven axisymmetric torsional oscillation physically preferred in a special range of small Prandtl number and its nonlinear properties at finite supercritical Rayleigh numbers. We shall also report a new nonlinear phenomenon discovered in the classical problem of thermal convection in a rapidly rotating, self-gravitating, internally heated fluid sphere that also undergoes weak precession.

Wall-bounded stably stratified turbulence at large Reynolds number

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Wall-bounded stably stratified turbulent flows are a common occurrence in many industrial and natural processes. Examples include cooling in nuclear reactors, fuel injection and combustion in gasoline engines, the dynamics of the nocturnal atmospheric boundary layer or the transport of organic species in the ocean. In this work, we focus on stably stratified turbulent channel flow at high shear Reynolds number Re_τ. We performed an extensive campaign of pseudo-spectral direct numerical simulations (DNS) of the governing equations (momentum and energy equations written under the OB approximation) in the shear Richardson number space $Ri_\tau = Gr/Re_\tau^2$, where Gr is the Grashof number. In particular, we fix the Reynolds number $Re_\tau = 1000$ and we change Gr so to cover a broad range of Ri_τ values. We recall that Re_τ is the ratio between inertia and viscous forces, whereas Ri_τ is the ratio between buoyancy and inertia forces. Our results of stratified turbulence indicate that the average and turbulent fields undergo significant variations compared to the case of forced convection, in which temperature is a passive scalar ($Ri_\tau = 0$). We observe that turbulence is actively sustained only near the boundaries, whereas intermittent turbulence, also flavored by the presence of non-turbulent wavy structures (Internal Gravity Waves, IGW) is observed at the core of the channel. This situation is clearly visible in Fig. 1, where temperature contours are used to visualized the flow structures on a $(x - z)$ streamwise section for the case $Ri_\tau = 0$ (top panel) and $Ri_\tau = 25$ (bottom panel). The flow goes from left to right and is bounded at the bottom and top wall. Internal waves are found in a narrow region around the channel centerline (Fig. 1, bottom panel) and constitute a sort of a thick interface (thermocline) that separates the channel into two parts, a top and a bottom one, which are almost independent and interact only slightly. Naturally, this alters also the overall transfer rates of momentum and heat, as well as the mixing efficiency of the flow. We believe that the present results may give important contributions to future turbulence parametrization and modeling in this field.

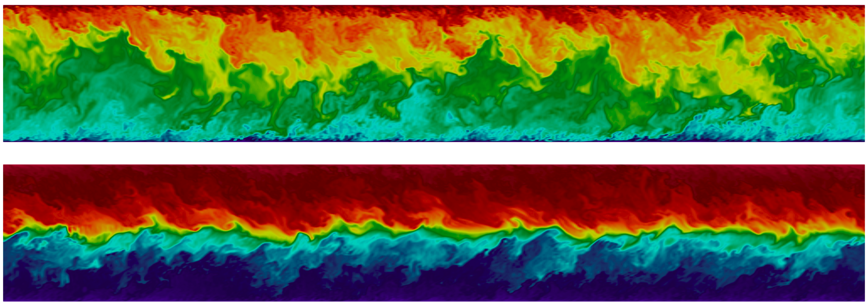

Figure 1: Contour map of the temperature field for $Ri_\tau = 0$ (top panel) and for $Ri_\tau = 25$ (bottom panel) on a streamwise section located at the center of the channel. The flow goes from left to right and is bounded at the top and bottom wall.

Impact of internal gravity waves on dynamics and transport in the stratosphere.

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In the terrestrial atmosphere, internal gravity waves (GWs) are a naturally occurring and ubiquitous, though intermittent (in the sense of large amplitude wave packets) phenomenon influencing its thermal and dynamical structure such as its angular momentum distribution. Also, GWs (orographic GWs (oGWs) in particular) are asymmetrically distributed around the globe. In the current generation general circulation models (GCMs), GWs are usually smaller than the model resolution and the majority of their spectrum must be parameterized. However, the intermittency and asymmetry of a spatial distribution of the resulting GW drag (GWD) is to some extent present also in the parameterization outputs (particularly for oGWD).
This presentation concerns the impact of spatio-temporaly intermittent GW forcing on the model middle atmosphere, with a special focus on the extra-tropical upper troposphere - lower stratosphere region (UTLS). UTLS is characterized by a strong interplay of chemical, physical and dynamical processes. To date, the representation of this dynamically active region in models frequently mismatches observations. The role of GWs for the UTLS transport and composition is poorly understood and the representation of GWs is one of the most uncertain aspects of climate modelling. In this study, the relationship between the Brewer-Dobson circulation and the zonally asymmetric GW forcing is revised (taking into account the compensation mechanism and validity of the downward control principle in particular). Further, the so-far omitted link between oGWD and the large-scale quasi-isentropic stirring and thereby tracer transport/trends in the UTLS is investigated. Especially, the relationship between finite amplitude and transient Rossby wave events and GW activity is investigated.
One of the main conclusions of this study is that the traditional GWD output in the recent GCMs in the form of zonal mean monthly mean data is not fully representative of the GWD distribution. It is argued that the traditional output prevents a proper analysis of the possible GW effects, as it can hide different impacts of the zonally asymmetric GWD distribution and intermittent, extreme GWD values.
As the GWs are currently acknowledged to impact the atmospheric composition predominantly by the induced vertical mixing, the mainly theoretical and modeling study is supplemented by satellite observations of stratospheric trace gas distributions with imprints of the GW induced vertical mixing. In this part of the study, as a side result, a novel method for atmospheric turbulence detection from radiosonde data based on evaluation of the validity of hydrostatic balance is introduced and evaluated.

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