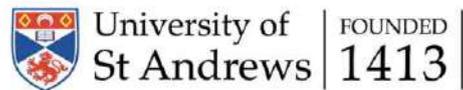


International Conference on Geophysical and Astrophysical Fluid Dynamics (ICGAFD)

23-25 June 2025, IUEM – Pole Numérique, Plouzané, France



BOOK OF ABSTRACTS



**International Conference on Geophysical and Astrophysical Fluid Dynamics (ICGAFD)
23-25 June 2025, IUEM – Pole Numérique, Plouzané, France**

DAY 1: Monday 23 June 2025

Time	Speaker	Title	Page in booklet
9:00-9:40		Welcome coffee	
9:40-9:50	Carton Xavier	Opening remarks	
Session I		Chaired by Prof David Dritschel	
09:50-10:10	Zavala-Sanson Luis	Self-organized states in rotating turbulence in an oceanic basin with topography: decaying and continuously forced flows	2
10:10-10:30	Brown Joshua	Nonlinear dispersive spiral waves in accretion discs	4
10:30-11:00		Coffee break	
Session II		Chaired by Dr Jan-Bert Flor	
11:00-11:20	Sugimoto Norihiko	Spontaneous gravity wave radiation in the Venus atmosphere	5
11:20-11:40	Hughes Stephen	A shallow water model of variability in Mars' polar vortices	6
11:40-12:00	Cope Laura	The Dynamics of Jovian Polar Cyclones	7
12:00-12:20	Tsang Yue-Kin	Oscillatory double-diffusive convection in a rotating spherical shell at low Rayleigh numbers	8
12:20-14:00		Lunch time + setting posters	
Session III		Chaired by Prof Joseph LaCasce	
14:00-14:20	Hay Hamish	Tidally-driven mean flows in icy satellite subsurface oceans	9
14:20-14:40	Chang Xu	Zonal flows driven by libration in rotating spherical shells	10
14:40-15:00	Kiernan Murray	Lunar tides of a liquid iron core beneath a basal magma ocean	11
15:00-15:20	de Vries Nils	Fully compressible simulations of mixed modes in evolved low-mass stars	12
15:20-15:50		Coffee break + posters	
Session IV		Chaired by Prof Jonas Nycander	
15:50-16:10	Favier Benjamin	A laboratory model for Jovian polar vortices	13
16:10-16:30	Sutyris Giorgi	Life cycles of coherent vortices and their transport properties in baroclinic zonal flows (online)	14
16:30-16:50	Riccardi Giorgio	Something about the time evolution of the Schwarz function of a vortex patch (online)	15

DAY 2: Tuesday 24 June 2025

Time	Speaker	Title	Page in booklet
Session V		Chaired by Dr Paul Billant	
09:00-09:20	Hajduk Hennes	Spin-up of a stratified ocean with topography	16
09:20-09:40	Deng Peng	Distinct Impacts of Topographic versus Planetary PV gradients on Baroclinic Turbulence	17
09:40-10:00	Lemasquerier Daphné	Experimental study of turbulent zonal flows interacting with local topography	18
10:00-10:20	Stanchieri Chiara	Jet formation in multi-layer fluid over topography	19
10:20-10:50		Coffee break + posters	
Session VI		Chaired by Dr Laura Cope	
10:50-11:10	Flor Jan-Bert	Vertical convection regimes in a three-dimensional cavity	10
11:10-11:30	LaCasce Joseph	Rossby waves over rough bathymetry	21
11:30-11:50	Aulnette Marine	Vertical velocities in laboratory surface vortices	22
11:50-12:10	Mokuenko Vincent	Topography-generated submesoscale coherent vortices near the mid-Atlantic ridge	23
12:10-14:00		Lunch time	
Session VII		Chaired by Dr Luis Zavala Sansón	
14:00-14:20	Oliver Marcel	The role of equatorial waves in spontaneous emission	24
14:20-14:40	Nycander Jonas	Steady baroclinic vortices radiating Rossby waves in vertically sheared flows	25
14:40-15:00	Barboni Alexandre	Relationship between mesoscale eddy surface temperature anomaly and its vertical structure : case study in the Arabian Sea.	26
15:00-15:20	Zoeller Victoria	An interaction mechanism sustaining near-equilibrium shielded geophysical vortices	27
15:20-15:50		Coffee break + posters	
15:50-16:30		Flash talks for posters (chaired by Dr Jean Reinaud)	
16:30-18:00		Poster session	
18:00		Cocktail	

DAY 3: Wednesday 25 June 2025

Time	Speaker	Title	Page in booklet
Session VIII		Chaired by Dr Daphné Lemasquerier	
9:00-09:20	Billant Paul	Mean flow generation in two-dimensional forced stratified turbulence: uprising of enslaved modes	42
09:20-09:40	Niu Zhaodong	Three-dimensional structure of anticyclonic vortices in a stratified rotating fluid	43
09:40-10:00	Reinaud Jean	Vortex vertical alignment over topography	44
10:00-10:20	Barabinot Yan	Defining Mesoscale Eddies Boundaries from in situ Observations and Theory	45
10:20-10:50		Coffee break + posters	
Session IX		Chaired by Dr Benjamin Favier	
10:50-11:10	Coppin Max	Experimental Observation of Oceanic Convection on the Coriolis Platform	46
11:10-11:30	Kafabad Hossein	Interaction of Near-Inertial Waves with an Anticyclone	47
11:30-11:50	Rouillet Guillaume	When GFD meets DDG	48
11:50-12:10	McKiver William	Exploring cyclone-anticyclone asymmetry using the balanced ellipsoidal vortex at finite Rossby number	49
12:10-14:00		Lunch time	
Session X		Chaired by Dr Patrice Le Gal	
14:00-14:20	Miller Lennard	The Impact of Stratification on Surface-Intensified Eastward Jets in Turbulent Gyres	50
14:20-14:40	Ding Shan-shan	Turbulent Energy Spectra in a Convectively Driven Baroclinic Flow	51
14:40-15:00	Kobe Simoons	Phytoplankton response to oceanic vortex perturbations	52
15:00-15:20	Alende Sofia	Characterizing Mixing-Length Growth and Melt Rates at the Ice-Ocean Interface	53
15:20-15:50		Coffee break + posters	
Session XI		Chaired by Prof Xavier Carton	
15:50-16:10	Crowe Matthew	Steadily propagating modons in 3D quasi-geostrophic models	54
16:10-16:30	Dritschel David	Why Surface Quasi-Geostrophy is a poor model	55
16:30-16:40		Concluding remarks	

LIST OF POSTERS (poster session Tuesday 22 June, 16:30)

Speaker	Title	Page in booklet
Ding Shan-shan	A Rapidly Rotating Baroclinic System: Insights into Large-Scale Structures in Astrophysical Systems	29
Flor Jan-Bert	Geometric internal wave focusing: from weak to strong viscous effects	30
Gostelow Luke	Vortex disruption in quasigeostrophic shallow-water MHD	31
Hu Xinniao	Impact of Deep Thermal Forcing on Jupiter's Baroclinic Instability and Jet Dynamics	32
Mishra Himanshu	Orientation dynamics of an ice crystal in cloud	33
Monville Remy	Thermal Image Velocimetry for experimental rotating fluid dynamics	34
Nath Anu	Unveiling a Novel Particle-Induced Instability in Shear Flows	35
Ravasse Raphael	Analytical study of instabilities in idealized shielded vortices	36
Saddier Louis	Bistable Ocean Circulation Beneath Antarctic Ice Shelves: Insights from idealized numerical simulations	37
Campagnoli Napolitano	Velocity and Kinetic Energy Decomposition of the Deep Western Boundary Current in a Semi-Enclosed Basin	39
Volorio-Galea Anastasia	Submesoscale SST fronts reconstruction	40
Geoffroy Gaspard	Diffusion of internal tides by geostrophic turbulence	41

Self-organized states in rotating turbulence in an oceanic basin with topography: decaying and continuously forced flows

Luis Zavala Sansón

Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE), México

The evolution of quasi-two-dimensional turbulent flows in a closed basin with topography in a rotating system is studied with numerical simulations based on a homogenous shallow-water model and laboratory experiments in a rotating tank. The basin is nearly flat in the central region and has a sloping coastal topography adjacent to the lateral walls. The configuration resembles an f -plane basin in the Northern Hemisphere (positive Coriolis parameter). Two problems are analysed: (i) the slow decay of an initially disordered flow and (ii) the evolution of a continuous and randomly forced flow. For the freely decaying flow, the main numerical and experimental results are the formation of a steady, anticlockwise flow around the basin that follows the topographic contours and, secondly, the spontaneous generation of an anticyclonic vortex at the nearly flat central part of the domain. This ‘preferred’ configuration was repeatedly found for arbitrary initial conditions. The well-defined current around the basin is associated with the direction of propagation of topographic Rossby waves along the contours of constant depth. The second problem concerns the evolution of an initial flow at rest that is continuously forced until reaching a quasi-stationary turbulent state. The resulting flow is disordered, but the total kinetic energy remains nearly constant. However, even in the presence of the random forcing protocol (with no preferential direction in time or space), the average flow always tends to the preferred configuration found for decaying flows. This result is clearly observed in both the simulations and the laboratory experiments. The results are discussed in light of recent numerical studies^{1 2 3} and oceanographic observations⁴ in different basins. The limitations of the idealised simulations and experiments are outlined, as well as recommendations for future studies

¹Solodoch et al., *J. Phys. Oceanogr.* **33**, 207-228 (2021)

²Zavala Sansón *Geophys. Astrophys. Fluid Dyn.* **116-3**, 159-184 (2022)

³LaCasce et al., *J. Fluid Mech.* **979-A32**, 1-31 (2024)

⁴Isachsen et al., *J. Phys. Oceanogr.* **51**, 2534-2550 (2003)

2D condensate from 3D waves

Sébastien Gomé¹, Anna Frishman¹,

¹ Department of Physics, Technion Israel Institute of Technology, 32000 Haifa, Israel

Rotation tends to homogenize flows, making them appear two-dimensional even under turbulent conditions. The 2D flow can self-organize into a large-scale structure called a condensate, similarly to strictly 2D turbulence. Such condensates, however, arise even when energy is injected into 3D modes, implying an energy transfer from 3D to 2D. At high rotation rates, 3D modes take the form of inertial waves, each carrying energy and a sign-definite helicity, and interactions are limited to wave resonances. However, exactly resonant interactions do not transfer energy from 3D to 2D modes. Two questions thus arise: (i) Why is energy transferred directionally *from* 3D to 2D modes in rotating flows? (ii) How is such energy transfer possible at high rotations? We answer these questions for the condensate state across different regimes using extensive numerical simulations and wave-mean-flow theory. We show that the answer to (i) is an (approximate) conservation law: at sufficiently high rotation, the remaining wave-condensate interactions conserve the waves helicity *separately for each sign*, explaining the energy transfer to the large-scale condensate. These interactions are however only approximately resonant, answering question (ii), and are gradually suppressed upon increasing rotation. In the other direction, decreasing the rotation rate gradually reintroduces wave-condensate interactions which break single-sign helicity conservation. These interactions take energy away from the condensate, while the conserving interactions still feed it. The condensate is then a product of counteracting fluxes, eventually reaching the so-called flux-loop state. Quantitatively, our theory reproduces the Rossby and Reynolds number dependence of the condensate amplitude in different regimes, Fig. 1(b).

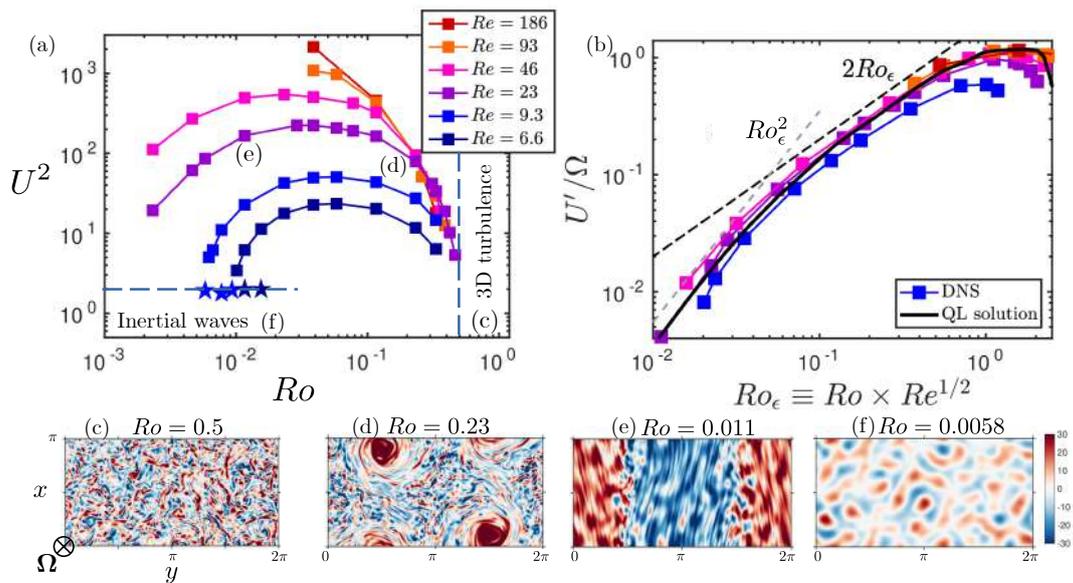


Figure 1: Spontaneously forming large-scale flows in rotating 3D turbulence. (a) The variation of normalized condensate energy with $Ro \propto 1/\Omega$ and Re . (b) The normalized condensate shear rate collapses as a function of Ro_ϵ (c-f) Flow visualizations at various values of Ro , at low rotation, and fixed $Re = 23$. (c) 3D turbulence. (d) array of 2D vortices ; (e) jets (f) 3D inertial waves (stars in (a))

Nonlinear dispersive spiral waves in accretion discs

Joshua J. Brown¹, and Gordon I. Ogilvie¹

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Discs of gas and dust in orbit about massive central bodies are ubiquitous in our universe. Planets embedded in protoplanetary discs, or black holes orbiting within AGN discs, excite steady in- and outgoing spiral waves resembling the wake shown in figure 1. The nonlinear evolution and shocking of these waves can have dramatic consequences for the disc's morphology as well as the evolution of the system as a whole, for example carving rings and gaps in the disc, and informing planetary orbital migration.

One important aspect of the problem which has yet received little attention is the role of linear dispersion in competing with and overcoming the effects of nonlinear steepening on spiral waves. We demonstrate a remarkable mathematical correspondence between these 2D steady spiral waves and simpler axisymmetric 1D unsteady waves. We show analytically and verify with simulations that in some cases dispersion is able to prevent the wave from shocking altogether, even in inviscid discs. This result has important consequences for the early life and evolution of young, small Earth-like planets.

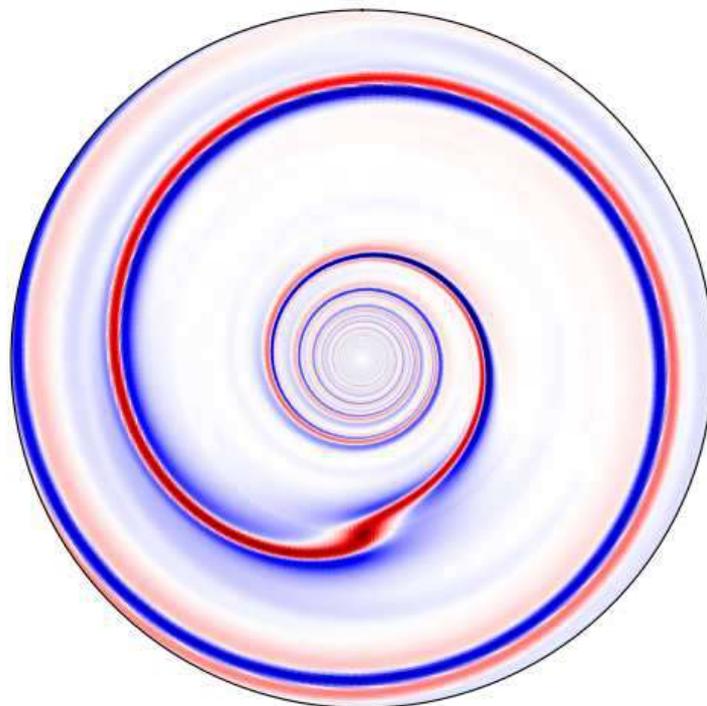


Figure 1: The density structure of the spiral wake excited by a disc-embedded planet from a hydrodynamic simulation.

Spontaneous gravity wave radiation in the Venus atmosphere

Norihiko Sugimoto¹, Yukiko Fujisawa¹, Hiroki Kashimura², Katsuyuki Noguchi³,
Takeshi Kuroda⁴, Masahiro Takagi⁵ and Yoshi-Yuki Hayashi²,

¹ Keio Univ., ² Kobe Univ., ³ Nara Women Univ., ⁴ Tohoku Univ., ⁵ Kyoto Sangyo Univ., Japan.

Gravity wave plays important roles in the terrestrial atmosphere because it transports momentum and energy globally. In the Venus atmosphere, small scale gravity waves are observed in the super rotation but their characteristics are not well understood. In this study, we have investigated small scale gravity waves reproduced in a high-resolution Venus general circulation model¹ (T639L260) with less than 20 and 0.25 km in the horizontal and vertical grid intervals, respectively. In the upper cloud layer (~70 km), the thermal tides are dominant sources in the low-latitudes², while the Baroclinic/barotropic waves are also sources in the mid- and high-latitudes (Fig.1). We will demonstrate that those gravity waves are spontaneously radiated from nearly balanced flows³ (Fig.2). It is also shown that the gravity waves affect the three-dimensional structure of the super-rotation and contribute to material mixing through their breaking processes.

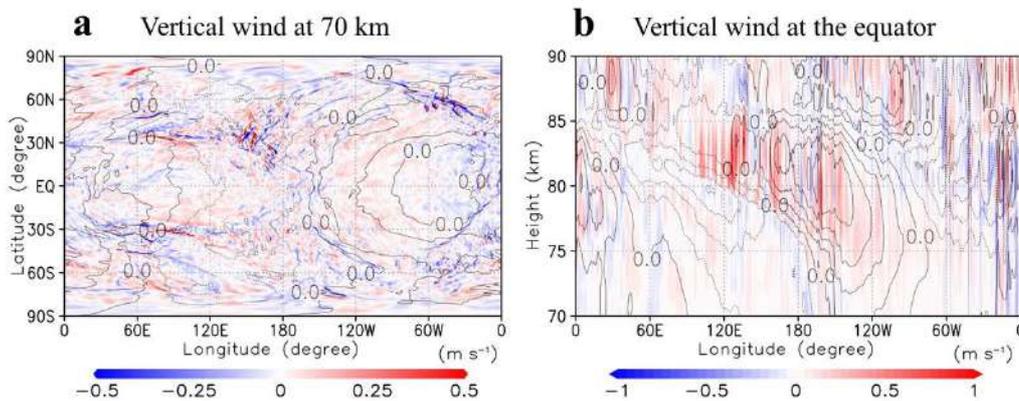


Figure 1: Vertical wind (a) at 70 km and (b) at the equator.

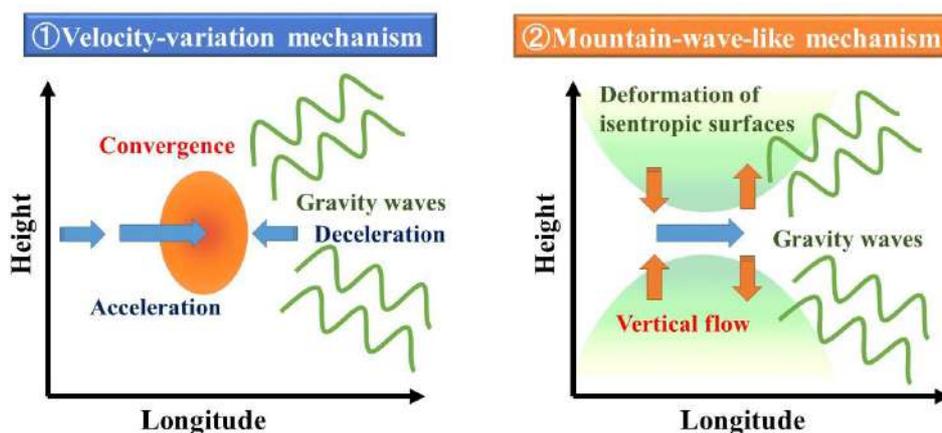


Figure 2: Schematic figure of spontaneous gravity wave radiation at the jet exit region: (1) Velocity-variation mechanism and (2) Mountain-wave-like mechanism

¹ Sugimoto et al., *Journal of Geophysical Research: Planets*, **119**, p1950–1968 (2014)
² Sugimoto et al., *Nature Communications*, **12**, 3682 (2021)
³ Yasuda et al., *Journal of the Atmospheric Sciences*, **72**, p957–983 (2015)

A shallow water model of variability in Mars' polar vortices

Stephen Hughes¹, William J. M. Seviour¹, Jemma Shipton¹ and Stephen I. Thomson¹

¹ University of Exeter, UK

The time averaged winter polar vortex on Mars has been observed to have an annular structure, with a potential vorticity (PV) local minimum at the pole and a surrounding region of higher PV. This structure is known to be barotropically unstable; latent heat released by condensation of atmospheric CO₂ is thought to be the major forcing mechanism responsible for maintaining it¹. Whilst the time-averaged polar vortex is seen to take a smooth annular structure, reanalysis data suggest the instantaneous polar vortex is spatially patchy with localised regions of higher and lower PV rotating around the pole². The large PV gradients on the edge of polar vortices typically form a strong mixing barrier, however it is not known whether this differs for a patchy polar vortex such as on Mars. Variations in the transport of dust and trace gases within Mars' polar regions due to its patchy polar vortex may help explain differing dust deposits within the polar ice layers.

Here we present results from a novel modelling approach, following the work of Seviour et al. 2017³ and Rostami et al. 2018⁴, aiming to represent a potential driver of polar vortex patchiness and its impacts on atmospheric mixing. The shallow water equations are solved on a sphere, using a new finite element model, Gusto, with additional terms to represent a zonally symmetric radiative forcing and spatially variable CO₂ condensation. The spatially variable 'latent heating' leads to increased PV patchiness within the polar vortex, when compared to a purely zonally symmetric forcing, as seen in Figure 1. A passive tracer is included in the model to allow measurements of horizontal transport across the polar vortex; Figure 1 demonstrates that a patchier polar vortex has higher cross-vortex mixing. The inclusion of the spatially variable forcing leads to larger variations in mixing properties for slightly altered vortex morphology, demonstrating that accurate representations of vortex patchiness may be required to explain past changes in Martian atmospheric mixing.

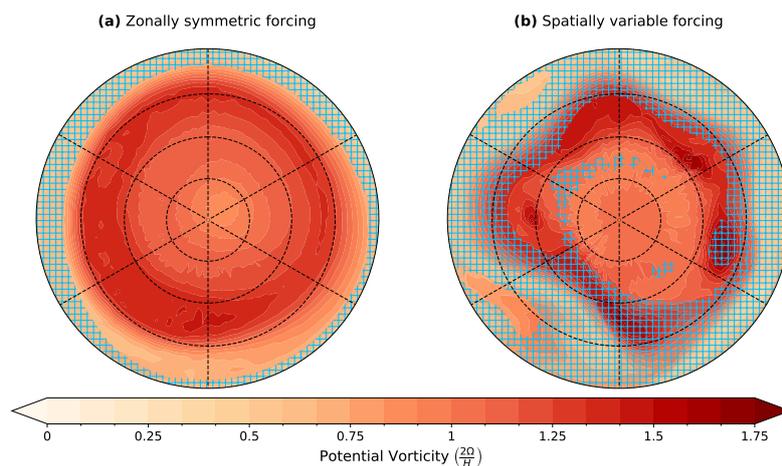


Figure 1: Polar stereographic projection, bounded at 50°N, of PV (colours) and advected tracer (hatching showing tracer concentrations above a threshold value) in a simulation with purely zonally symmetric forcing (a), and additionally with spatially variable 'CO₂ condensation' (b). The polar vortex shown in (b) shows higher PV patchiness, and increased mixing of the tracer into the vortex.

¹Toigo et al., *Geophysical Research Letters* **44**, 71 (2017)

²Waugh et al., *Annual Review of Fluid Mechanics* **55**, 265 (2023)

³Seviour et al., *Journal of the Atmospheric Sciences* **74**, 1533 (2017)

⁴Rostami et al., *Icarus* **314**, 376 (2018)

The Dynamics of Jovian Polar Cyclones

Laura Cope¹, Stephen Thomson¹

¹ *Department of Mathematics and Statistics, University of Exeter*

Polar vortices are observed in the atmospheres of most solar-system planets, arising as a single cyclone centred on or close to the pole. In contrast, Jupiter's polar vortices have an unprecedented structure. As revealed by NASA's Juno spacecraft, they consist of geometric patterns of cyclonic vortices surrounding a central cyclonic vortex at the pole. These crystalline structures were not predicted prior to being observed, and the mechanisms explaining their formation and evolution remain poorly understood. One possible mechanism is that moist convection produces small vortices in the polar regions, with the cyclones then migrating polewards via the 'beta-drift' mechanism and merging. Nevertheless, models including these processes do not spontaneously produce polygonal patterns like those on Jupiter.

In contrast, this study investigates the stability of an initialized pattern of fully formed polar vortices subjected to these small-scale short-lived processes. This forced-dissipative system is modelled using the shallow-water equations describing a single layer of fluid on a polar gamma-plane. The initialized cyclones are subjected to a stochastic forcing with a short decorrelation time and the factors affecting their stability and time-evolution are studied. These include their degree of shielding (an anticyclonic ring around each cyclone), their depth and the properties of the forcing, in addition to the role of potential vorticity mixing.

Oscillatory double-diffusive convection in a rotating spherical shell at low Rayleigh numbers

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Newcastle University, UK

We consider a fluid whose density depends on two scalar quantities with very different diffusivities (e.g. temperature and salinity). If the two scalars give rise to opposing buoyancy forces, instabilities may occur in counter-intuitive manners. In this talk, we focus on the setup that the fast-diffusing scalar tends to destabilise the system while the slow-diffusing one is stabilising (e.g. warm and more salt at the bottom). This regime is sometimes known as oscillatory double-diffusive convection (ODDC). Motivated by situations in the interiors of gas giants and stars, we investigate ODDC in a rotating spherical shell. Our fully nonlinear numerical simulations show that the inclusion of the slow-diffusing, presumably stabilising scalar can promote the onset of convection in the presence of rotation. Moreover, diverse flow patterns, such as the localised spiral columns shown in Figure 1, are found in the long-time statistically steady state. Theoretically, we extend Busse's approach (1986) in capturing the essential physics of the spherical system using a cylindrical annulus model. By disentangling the different linear modes in this model, we explain qualitatively the interesting features found in the spherical shell geometry.

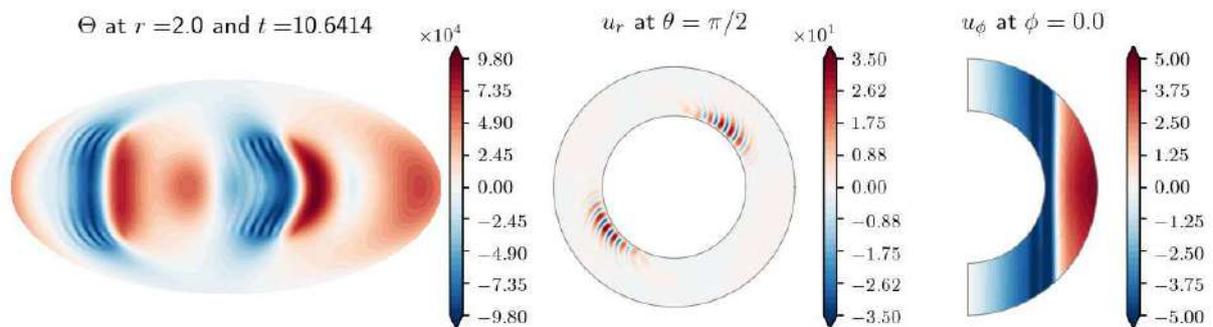


Figure 1: Patterns of (fast-diffusing) temperature perturbation (left), radial velocity (middle) and zonal velocity (right) exhibit in oscillatory double-diffusive convection in a rotating spherical shell for a set of parameters near the onset.

Tidally-driven mean flows in icy satellite subsurface oceans

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Mean flows are fundamental to global oceans and atmospheres. They typically manifest as zonal (east–west) jets and meridional (north–south) flows that transport heat, mass and chemistry. In the context of icy satellites such as the Jovian moon Europa, understanding these flows may be vital for interpreting the rotation rate of the ice shell and meridional variations in ice thickness. Here we show how diurnal tides—an oscillating flow—generate a secondary mean flow in Europa’s ocean through tidal wave–wave interactions¹.

Oscillating currents in subsurface oceans forced by libration and/or tides are generally investigated in the linear limit, an assumption that prevents any net motion of individual fluid parcels over an oscillation period. Here, we relax this assumption and develop a theory that predicts the emergence of mean currents driven by any periodic forcing. The theory, derived in the context of a global, uniform, shallow ocean, constitutes a set of mean flow equations forced by non-linear eddy fluctuations. The latter are the canonical, periodic tidal currents predicted by the Laplace Tidal equations.

We show that the degree-2 tide-raising potential due to obliquity and/or orbital eccentricity can drive time-averaged currents with zonal wavenumbers from 0 through 4. The most prominent of these is a retrograde zonal jet driven by the obliquity-forcing potential. We determine approximate analytical solutions for this jet, demonstrating that it arises from a meridional vorticity transport imbalance between the tidal oscillations and a weak north–south mean flow. Assuming Cassini state obliquities, this jet has speeds ranging from 0.01–1 mm s⁻¹, which can exert torques up to roughly 10¹⁵ N m at the ice–ocean interfaces of Europa, Callisto, Titan, and Triton. Depending on the viscosity of the ice shell, these torques could reorient the ice shells of these moons by tens to potentially hundreds of meters a year. Thinner or stably stratified global oceans can experience much faster mean currents.

When considered simultaneously, we find that eccentricity and obliquity forced oscillating flows couple to generate an unusual permanent wavenumber-1 and -3 meridional flow. These flows have the potential to induce true polar wander of icy shells over time.

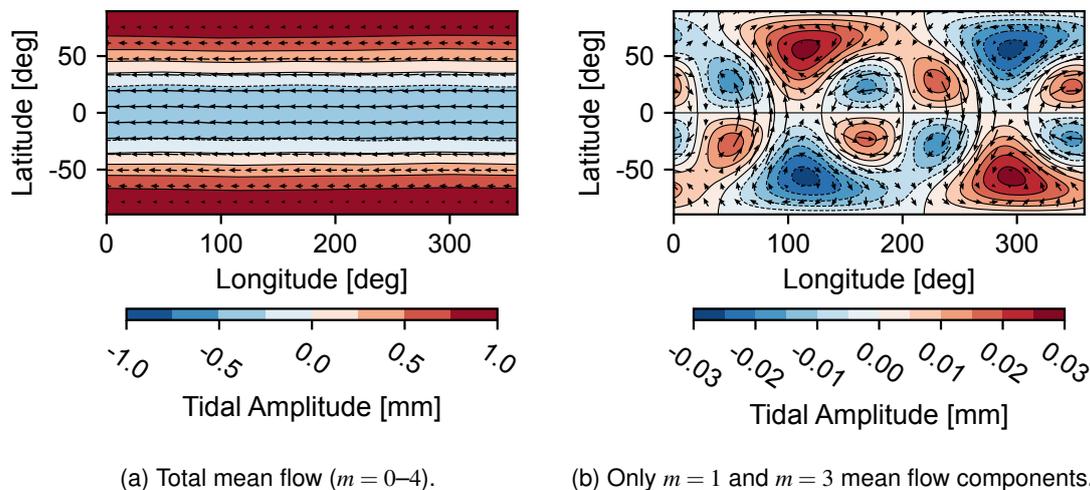


Figure 1: Time-averaged flows in a European ocean generated by simultaneous eccentricity ($m = 0, 2$) and obliquity ($m = 1$) forcing.

¹Hay et al., *JGR: Planets* **129**, e2024JE008408 (2024).

Zonal flows driven by libration in rotating spherical shells

Xu Chang¹, Jiyang He^{1,2}, Benjamin Favier¹ and Stéphane Le Dizès¹

¹ Aix Marseille Univ, CNRS, Centrale Med, IRPHE, France, ² Dept. Ocean Science, HKUST, China

This work investigates the weakly nonlinear dynamics of internal shear layers and the mean zonal flow induced by the longitudinal libration of an inner core within a rotating spherical shell. Building on the work of He et al.¹, who focused on linear dynamics as shown in figure 1(a), we adopt a similar setup to explore the nonlinear regime using both asymptotic theory and numerical simulations. Typical numerical results for the meanflow are shown in figure 1(c). A specific forcing frequency of $\hat{\omega} = \sqrt{2}\hat{\Omega}$, where $\hat{\Omega}$ denotes the rotation rate, is used to obtain a closed rectangular path of characteristics for the inertial wave beam generated at the critical latitude. Our research reveals that nonlinear interactions are predominantly localized around regions where the wave beam reflects on the boundary, as demonstrated in the zoom-in view in figure 1(b) showing the localized nonlinear forcing². We derive scaling laws governing the width and amplitude of nonlinear interactions: the width scales as $E^{1/3}$, while the amplitude scales as $E^{-1/6}$ in the beam interaction region, in general. However, near the rotating axis, where the singularity of the self-similar solution becomes more pronounced, the amplitude exhibits a scaling in $E^{-1/2}$. In addition, our study also examines the Ekman scaling laws of the different meanflow bands, as summarized in figure 1(d). Through comparison with numerical simulations, we validate the theoretical predictions of the asymptotic framework, observing good agreement as the Ekman number decreases.

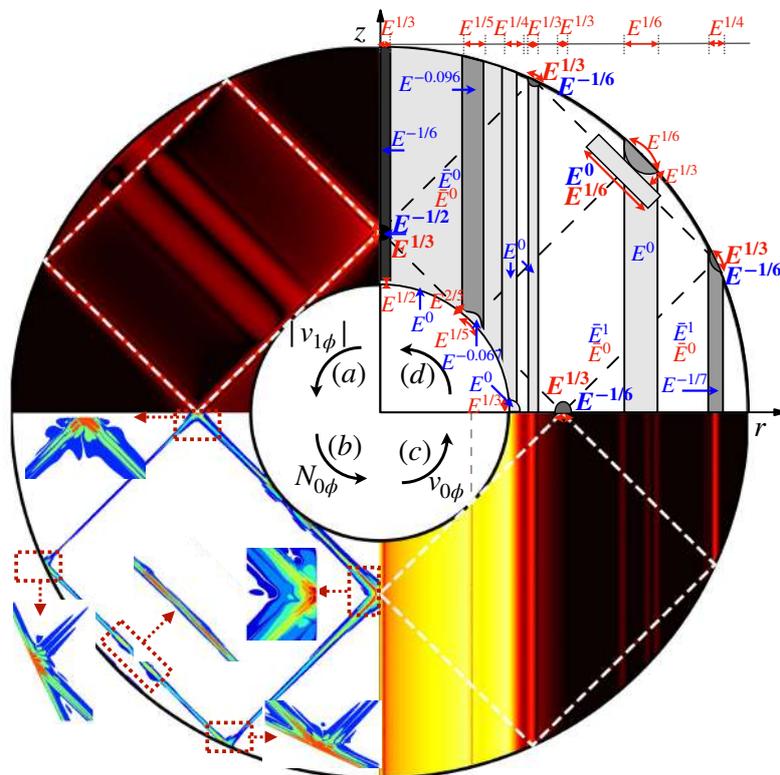


Figure 1: (a) Contour map of the linear harmonic solution of the azimuthal velocity $v_{1\phi}$, (b) Steady Reynolds stress derived from the linear velocity $N_{0\phi} = v_{1\phi} \cdot \nabla v_{1\phi}^* + c.c$ with zoom-in views at the local beam interaction regions, (c) Contour map of the nonlinear mean flow azimuthal velocity $v_{0\phi}$, the computations are performed for Ekman number $E = 10^{-10}$ and (d) Ekman scaling law of the nonlinear mean flow $v_{0\phi}$.

¹He et al., *J. Fluid Mech.*, **939**, A3 (2022)

²Le Dizès, *J. Fluid Mech.*, **899**, A21 (2020)

Lunar tides of a liquid iron core beneath a basal magma ocean

Murray Kiernan¹, Hamish Hay², David Rees Jones¹, James Bryson² and Richard Katz²

¹ University of St Andrews, UK, ² University of Oxford, UK

The tidal potential of an orbiting moon can perturb the immiscible interface between a liquid metal core and a basal magma ocean surrounded by a solid outer mantle, driving flows within the core. Could such flows provide the turbulent kinetic energy required to drive a dynamo and create a magnetic field?

We develop a two-layer, self-gravitating viscous fluid model of the system in which the density and viscosity of the fluids are constants, and the Coriolis force is neglected. The equations are linearized about a hydrostatic base state. The periodic gravitational forcing associated with the tidal potential due to the equatorial, circular orbit of the Moon perturbs the position of the core-mantle boundary (CMB) and drives a strong shear flow around the CMB, as shown in Figure 1. We explore the sensitivity of the flow to the key dimensionless parameters of the system, including the Reynolds number, the orbital frequency and the magma ocean thickness.

We analyse the properties of the flow, including resonances; CMB ellipticity; kinetic and potential energy, and interpret these properties in relation to the standard criteria for driving the geodynamo. We show that this flow may provide a mechanism for the geodynamo early in Earth history, prior to formation of the inner core. This model may also be relevant for planetary bodies large enough to form a basal magma ocean, and where one or more moons are present.

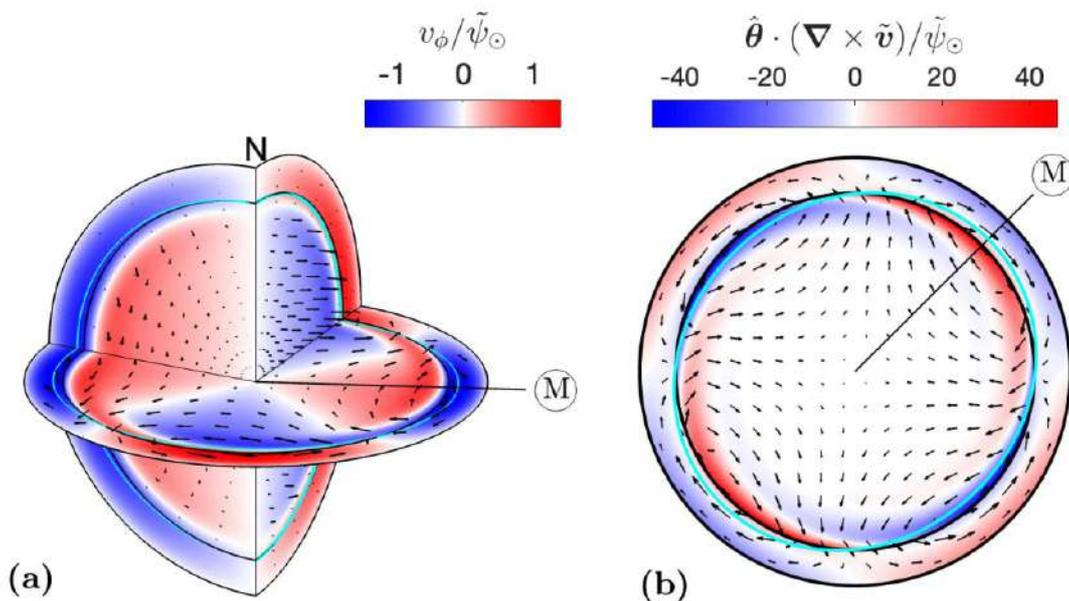


Figure 1: (a) Slices of the flow with colours denoting the azimuthal velocity component; (b) Equatorial plane with colours denoting the strength of the radial derivative of the azimuthal velocity. The cyan curve is an exaggerated depiction of the CMB displacement, and the position of the moon is denoted by an encircled M.

Fully compressible simulations of mixed modes in evolved low-mass stars

Nils de Vries¹, Isabelle Baraffe¹, and Thomas Guillet¹

¹ *University of Exeter, UK*

Sound waves in the convective interior of evolved stars can couple to internal gravity waves in the star's radiative regions, resulting in standing modes throughout the stellar interior, known as mixed modes. There are numerous observations of such mixed modes in evolved stars, which probe features of the deep interior such as the core rotation rate. These mixed modes have up to now not been identified in hydrodynamical simulations. I will present the first simulations revealing the presence of mixed modes in $1.3M_{\odot}$ fully compressible evolved star models. Furthermore, I will attempt to obtain the amplitudes of the mixed modes in our simulations, in an effort to constrain the resulting angular momentum transport, thought to be one of the explanations for the smaller than expected difference in rotation rates between the core and envelope.

A laboratory model for Jovian polar vortices

Djihane Benzeggouta¹, Benjamin Favier¹, Michael Le Bars¹

¹ Aix Marseille Univ, CNRS, Centrale Med, IRPHE, Marseille, France

We present an experimental model where three equivalent cyclonic vortices are generated in the upper-layer of a two-layer density-stratified system in rotation. The cylindrical tank is filled with salty water and a thin fresh water layer is added at the top before rotation is imposed. The upper free surface is paraboloidal due to the balance between centrifugal and pressure forces leading to an effective β effect. Stable long-lived vortex clusters are experimentally observed after a transient drift of each cyclone towards the center of the rotating tank, as seen in Figure 1.

The experimental results are coupled with a toy-model where the radial equilibrium of the vortex cluster is fully determined by a balance between an attractive force (β -drift) and a repulsive force (cumulative effect from neighboring vortices). Experimental equilibrium distances are consistent with the toy-model results. The latter further shows that the larger the number of vortices, the farther they equilibrate, as observed experimentally.

The drift of the experimental vortex cluster highly correlates with their radial equilibrium distance. When the vortices equilibrate far from each other, they drift westward because of the β -drift mechanism, as observed on Jupiter. When they are close to each other, they strongly feel the mutual advection by their neighboring vortices resulting in an eastward drift.

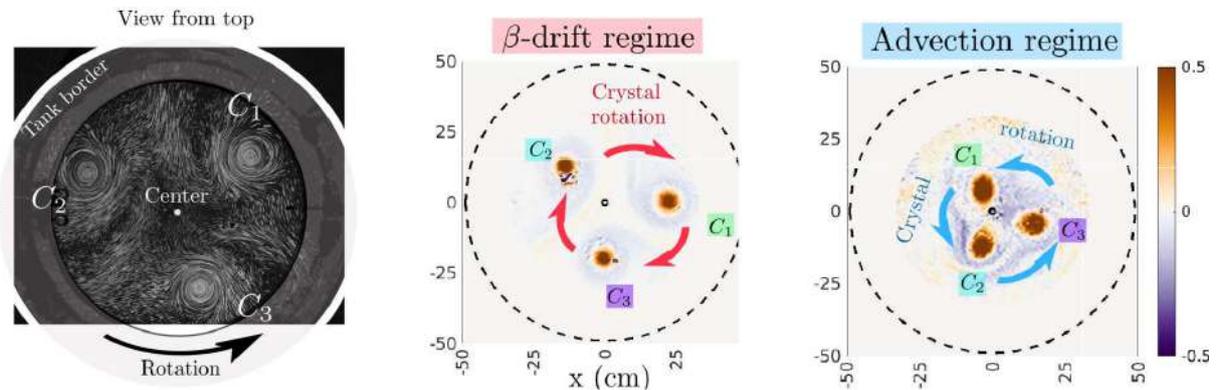


Figure 1: Left: Top view of the experiment from the rotating frame of reference, with floating PIV particles and long-time exposure of 0.5s. Right: Vorticity fields normalized by the maximum vorticity in the tank at two successive times during each regime. In the β -drift regime, the vortex cluster performs a drift towards the West (opposite direction to the rotation of the tank). In the advection regime, the vortex cluster performs a slower drift towards the East (same direction as the rotation of the tank).

Life cycles of coherent vortices and their transport properties in baroclinic zonal flows

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The fundamental differences in the dynamics of mesoscale vortices in eastward mean flows in mid-latitude ocean gyres and in westward return flows have been revealed in¹. In contrast to eddy behavior in eastward flows, a systematic meridional drift of eddies in westward flows results in poleward expulsion of cold-core cyclones and equatorward expulsion of warm-core anticyclones from the unstable zone with a negative potential vorticity gradient. Consequently, heat can be transferred by upper ocean vortices intrinsically coupled with deep opposite sign partners (Figure 1, left panel). Such structures can drift further through the stable zone with positive potential vorticity gradients in both layers. This mechanism of lateral transfer is not captured by local models of homogeneous turbulence. The crossflow drift is related to the hetonic coupling of the upper vortices with opposite sign deep eddies shifted eastward. The abyssal vortices can be viewed as lee Rossby waves induced by their upper-layer partners and described analytically in the vicinity of latitude of marginal stability (Figure 1, right panels). Here, we analyze the life cycles of such hetonic structures, emerging in baroclinically unstable zone, pulsating and saturating when approaching locally stable regions. The presented results indicate that subtropical regions with westward return flows in the upper layer favor long-distance heat transport by spatially coherent eddies in accordance with observations and motivate the development of non-local parameterizations of eddy transport.

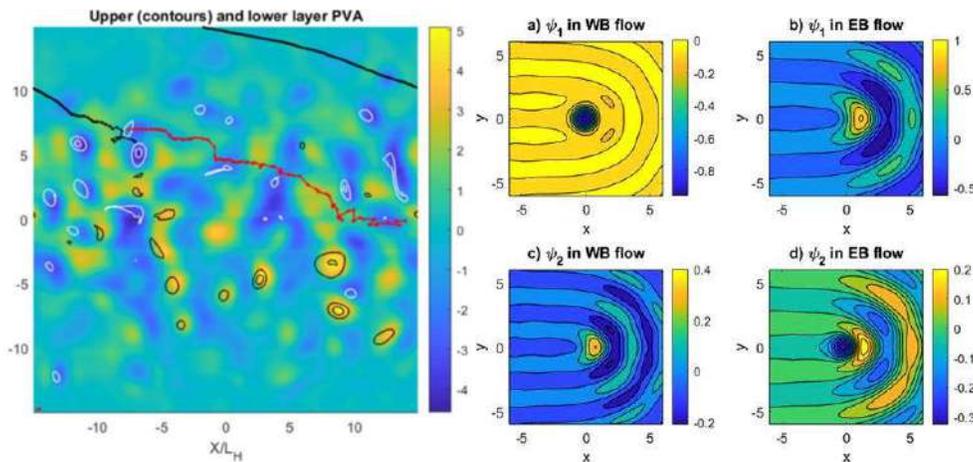


Figure 1: The left panel: The typical cyclone trajectory superimposed by potential vorticity anomaly (PVA) in the upper and lower layers at the time when the red curve ends. The right panels: Geostrophic streamfunctions in the inviscid analytical solutions for marginally stable two-layer westward (WB) and eastward (EB) flows

¹ G.G. Sutyrin et al., *Physics of fluids*, **34**, 126605 (2022)

Something about the time evolution of the Schwarz function of a vortex patch

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This contribution concerns some small achievements obtained in investigating the self-induced motion of a planar, uniform (with vorticity level ω) vortex P in an inviscid fluid. This flow is translated in terms of Complex Analysis by using the Schwarz function Φ generated by the vortex boundary: in any $x \in \partial P$, $\Phi(x)$ gives the conjugate point \bar{x} , while outside that curve it is defined via analytic continuation (a sibiylle procedure, but it will be explained below). About this fundamental function, it will be here considered just the time evolution of its internal singular set, assumed to be a branch cut (\mathcal{BC}_i) at any time. It starts from the branch point y_1 and ends at the other branch point y_2 , both internal to P . Φ experiences the finite jump $[\Phi](y)$ across any point y on it. Furthermore, if it is equipped with the density of circulation (τ is the unit tangent vector) $\gamma = -\omega \tau [\Phi]/(2i)$, it induces the conjugate velocity (s is the arclenght on \mathcal{BC}_i):

$$\bar{u}(x) = \frac{1}{2\pi i} \int_0^\ell ds \frac{\gamma[y(s)]}{x-y(s)}$$

in any x outside P (and on ∂P), that is identical to the one induced by the vortex itself! It is now clear why the motion of \mathcal{BC}_i , as well as the corresponding time evolution of $[\Phi]$, play a crucial role in the self-induced vortex dynamics.

The analytic continuations of the vortex velocity (U) and of its conjugate (\bar{U}) are built as

$$U(x) = \frac{\omega}{4\pi} \int_{\partial P} dx' \partial_{x'} \Phi(x') \frac{x'-x}{\Phi(x')-\Phi(x)}, \quad \bar{U}(x) = \frac{\omega}{4\pi} \int_{\partial P} dx' \frac{\Phi(x')-\Phi(x)}{x'-x} \quad (1)$$

and the time evolution of the Schwarz function $\Phi(x;t)$ is investigated by means of the initial value problem:

$$\begin{cases} D_t \Phi = \partial_t \Phi + U \partial_x \Phi = \bar{U} \\ \Phi(\xi;0) = \xi \end{cases} \quad (2)$$

that is posed for any ξ belonging to a suitable neighbourhood of $P(0)$ and uses both functions (1). It allows us to evaluate the time derivative of $[\Phi]$ in terms of the jumps of the convective term $[U \partial_x \Phi]$ and of the conjugate velocity $[\bar{U}]$. The speed $w(y)$ of the point $y \in \mathcal{BC}_i$ follows as

$$[\Phi] w = [L] + \left(\partial_t - \frac{\omega}{2i} \right) [\Psi], \quad (3)$$

where $[L]$ arises from the jump of the convective term of (2), and Ψ is the primitive of Φ ($\Phi = \partial_x \Psi$) that vanishes in y_1 . The speed (3) takes very significant forms in correspondence to the endpoints y_1 and y_2 of \mathcal{BC}_i .

In the paper ¹ the building of Φ , *i.e.* the analytic continuation of \bar{x} outside ∂P , was performed by expanding the map $z \mapsto x$ from the unit circle \mathcal{C} to ∂P in a truncated Laurent series. This was the simplest possible choice, even if there were accuracy problems due to the need of a threshold on the coefficients in its singular part (the ones smaller than the threshold were neglected). At the present time, the handling of the speed (3) without employing Laurent series is investigated. The use of external and internal Cauchy integral representations of the map $\mathcal{C} \rightarrow \partial P$ seems to be more suitable, once the following particular choice of \mathcal{BC}_i is made. Named as z_1 and z_2 the preimages of y_1 and y_2 , respectively, \mathcal{BC}_i is taken as the image of a circle internal to \mathcal{C} , centered at $(z_1 + z_2)/2$ and having radius $|z_1 - z_2|/2$. The preimages z_1 and z_2 are endpoints of a diameter of the above circle, and the two sides of \mathcal{BC}_i are images of the two corresponding semicircles. Results of this approach will be discussed in the talk.

¹Riccardi, *Geophysical & Astrophysical Fluid Dynamics* 118-3, 183-227 (2024)

Spin-up of a stratified ocean with topography

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Quasi-geostrophic (QG) equations are commonly used for numerical modeling in physical oceanography. These systems are generally nonlinear, baroclinic, and feature topographic terms to model the effects of the ocean floor. In earlier studies, e. g., [1, 2], our group explored the effects of bathymetry for various problem settings, using mostly two-layer QG systems. In this work, we extend the vertical discretization to an arbitrary number of layers based on consistent and realistic exponential density stratification. The *hydra* code used for the numerical simulations in this study is based on *contour advection*, a semi-Lagrangian technique for evolving potential vorticity (PV).

We employ *hydra* to study the spin-up of a stratified oceanic basin by wind forcing. The wind-stress curl is chosen such that a pair of gyres (subtropical and subpolar) is forced to appear. Depending on the parameter regime, the forcing may lead to energy growth up to the point that the gyres become unstable at which point the energy levels off. In other regimes, we observe the appearance of a gulf-stream like meandering jet separating the two gyres. In the three-layer case, we obtain PV homogenization in the middle layer, see also [3].

Next we study how these flat-bottom results change upon the inclusion of topography. To this end we use both monoscale and realistic (random data with a k^{-2} -spectrum) bathymetry of varying amplitude h . We observe that for high values of h , the lowest layer becomes locked to topography at roughly the same value of h for the different types of topography under investigation. In these cases, the upper layers are also affected, albeit without drastically changing the character of the upper-layer flow compared to the flat bottom results.

This study provides new perspectives on the classical work [4] and its follow-up [5] (where topography was also considered), in which similar problems were studied theoretically. A first important difference in our experiments, is the transient nature of the flow. In fact, based on the energetics of the problem, one cannot hope to approach a steady state in our 2D multilayer-QG setting. To avoid blow-ups of energy and for realism, we include bottom Ekman drag in our model, which is another effect that has been missing in earlier works.

References

- [1] A. PALÓCZY, J. H. LACASCE (2022) *Instability of a surface jet over rough topography*. J. Phys. Oceanogr. **52**: 2725–2740, doi:10.1175/JPO-D-22-0079.1
- [2] J. H. LACASCE, A. PALÓCZY, M. TRODAHL (2024) *Vortices over bathymetry*. J. Fluid Mech. **979**: A32, doi:10.1017/jfm.2023.1084
- [3] P. B. RHINES, W. R. YOUNG (1982) *Homogenization of potential vorticity in planetary gyres*. J. Fluid Mech. **122**: 347–367, doi:10.1017/S0022112082002250
- [4] D. L. T. ANDERSON, A. E. GILL (1975) *Spin-up of a stratified ocean, with applications to upwelling*. Deep Sea Res. **22**: 583–596, doi:10.1016/0011-7471(75)90046-7
- [5] D. L. T. ANDERSON, P. D. KILLWORTH (1977) *Spin-up of a stratified ocean, with topography*. Deep Sea Res. **24**: 709–732, doi:10.1016/0146-6291(77)90495-7

Distinct Impacts of Topographic versus Planetary PV gradients on Baroclinic Turbulence

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The impacts of topographic versus planetary potential vorticity (PV) gradients on fully-developed geostrophic turbulence are often treated as dynamically equivalent in theoretical understanding and parameterizations of ocean mesoscale turbulence. Using a suite of homogeneous, two-layer quasi-geostrophic (QG) turbulence simulations, we identify similarities and distinctions of topographic versus planetary PV gradients in modulating turbulent eddy energy and fluxes. We show that, while an elevated background PV gradient can suppress geostrophic turbulence, a positive (negative) bottom slope with respect to the orientation of isopycnal slope barotropitizes (de-barotropitizes) the turbulent energy at large scales, which contrasts with a dynamically inert planetary PV gradient in the mode-wise energy transfer. Then, in the presence of weak bottom drag, a positive slope energizes large-scale along-slope jets and limits small-scales barotropic eddies, both of which yield stronger eddy suppression effects than from a planetary PV gradient; by contrast, a negative slope hinders along-slope jet formation by enhancing the dual energy cascade cycling, which alleviates the topographic suppression on eddies. In the presence of strong bottom drag, a positive slope elevates barotropic eddy energy, which further enhances the eddy-driven fluxes; by contrast, a negative slope confines turbulent energy to the baroclinic mode, which is strongly damped, causing further weakened turbulent energy and eddy fluxes. A flow regime captured by linear QG theories also emerges as the turbulent energy cascade is jointly suppressed by negative slopes and strong bottom drag. This study provides insights into parameterizing mesoscale eddy effects over sloping bathymetry in predictive ocean models.

Experimental study of turbulent zonal flows interacting with local topography

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Zonal jets are coherent east-west winds or currents observed –or expected to emerge– in many planetary fluid layers, from the Earth’s oceans and atmosphere, to the atmospheres of gas giants, the sub-surface oceans of icy moons and the liquid metallic cores of telluric planets. In many of these systems, zonal jets interact with a solid boundary with topography: the bathymetry in Earth’s oceans is known to influence the dynamics of the Antarctic Circumpolar Current, flows in liquid cores interact with the topography at the Core-Mantle boundary, and icy moon oceans are in direct contact with a global ice crust of spatially varying thickness.

In this talk, I will present laboratory experiments to study the interaction between turbulent zonal jets and a local topography. We use the Coreoboloid device at UCLA¹ to robustly produce turbulent zonal jets. The setup is a 75cm-diameter water tank rotating at speeds up to 72 revolutions per minute. The deflection of the free surface due to the fast rotation provides a strong topographic β -effect. The flow is forced by thermal convection, driven by starting the experiment with hot water, and cooling the inner cylinder with a block of ice. To simulate a local topography, we attach acrylic disks of different radii and heights on the bottom plate. We visualise the flow using 1) a thermal infrared camera to image the temperature field at the free surface 2) particle image velocimetry (PIV) on a horizontal laser plane and 3) ultrasonic doppler velocimetry (UDV) along three chords. Preliminary results show the formation of stationary Rossby waves downstream of the topography (Figure 1), that feed back on the amplitude, number and position of zonal jets.

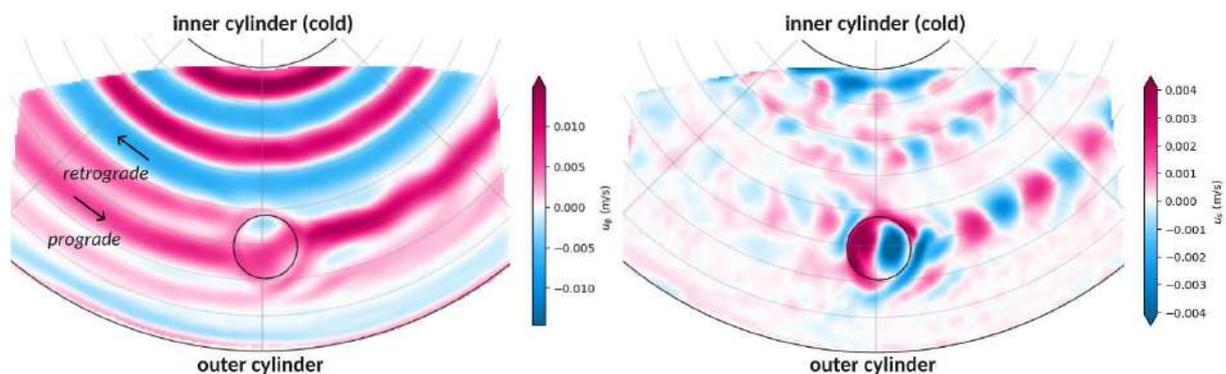


Figure 1: Time-averaged velocity fields obtained from PIV in a typical experiment at 72 rpm with a 6cm-wide, 4.5cm-high topography. The black circle is the horizontal position of the topography. Only a fraction of the total cylinder is visible. **Left:** Azimuthal component of the velocity. Red is prograde (same direction as the background rotation), blue is retrograde. **Right:** Radial component of the velocity. Red is outward, blue is inward.

¹Lonner et al., *JGR Planets* **127**(10), e2022JE007356 (2022)

Jet formation in multi-layer fluid over topography

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Zonal (east–west) jets are characteristic of many geophysical and planetary systems. On Jupiter, they manifest as strong zonal flows between its visible bands. In Earth’s atmosphere, similar jets occur near the tropopause. The Antarctic Circumpolar Current (ACC), the only oceanic current that can be modeled reasonably well with zonal jets, has marked density fronts at the surface, reflecting three distinct zonal jets. These jets are unstable, leading to meandering patterns and generating eddies. As such, jets play a central role in the dynamics of their respective environments.

This project investigates the formation of jets in the ACC, with a focus on the influence of bottom topography on jet structure.

The model used is Geophysical Flows¹. This model solves the multi-layer quasi-geostrophic equations on a beta plane, with and without bottom topography of various type (idealized and realistic). In this context, jet formation was initially studied in a two-layer, flat-bottom case. An additional layer was then introduced to help isolate the direct effects of bottom topography and allow for instability in the upper two layers.

Figure 1 shows jet formation in a two-layer channel with a flat bottom. The first row presents the potential vorticity of the top and bottom layer, from left to right. The second row shows the streamfunction of the two layers.

This research clarifies jet formation and the scales involved, contributing to a better understanding of the dynamics in the ACC. As the ACC connects the three main ocean basins, the work has implications for understanding the role of the ocean in the Earth’s climate system.

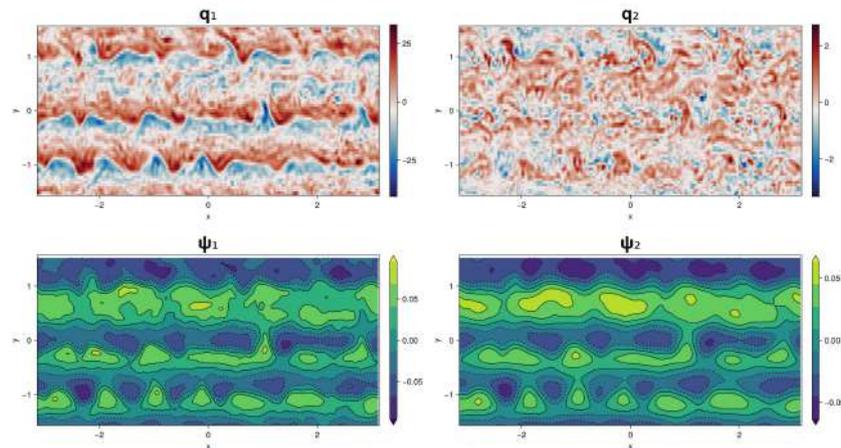


Figure 1: Jets in a 2 layer case, with flat bottom. The first row shows the potential vorticity, whereas the second row the streamfunction. The left column represents the first layer, while the right column the bottom layer.

¹Navid C. Constantinou and Gregory LeClaire Wagner and Lia Siegelman and Brodie C. Pearson and André Palóczy. GeophysicalFlows.jl: Solvers for geophysical fluid dynamics problems in periodic domains on CPUs & GPUs, Journal of Open Source Software, (2021)

Vertical convection regimes in a three-dimensional cavity

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In this study vertical convection as induced by the heating and cooling of two opposed vertical boundaries of a rectangular cavity is considered. In a former study (Khoubani et al, *J. Fluid Mech.* 2024) the linear stability of the steady two-dimensional flow at Rayleigh numbers of $O(10^8)$ was investigated as a function of the Prandtl number and the height-to-width aspect-ratio, A , of the domain. For the leading linear mode, six different flow regimes occur which depend on :1) the presence of circulation in the entire cavity; 2) the detachment of the thermal layer from the boundary or corner regions and 3) the oscillation frequency relative to the natural frequency of oscillation in the stably temperature-stratified interior, allowing for the presence of internal waves or not. A transition in regimes was marked by a dramatic change in oscillation frequency at $Pr \approx 0.55$ and $A < 2$, whereas aspect ratio and Prandtl number appeared to have comparable effects on circulation and stratification.

In this experimental and numerical study, we explore alike regimes and oscillation frequencies for relatively high Rayleigh-numbers and three dimensional flows. Some of the modes that are present at the onset of instability in 2D flows remain to some extent dominant over the three dimensional modes that are redundant at higher Rayleigh numbers. Preliminary results showed indeed a remarkable presence of an internal wave field (see Figure 1) that has some resemblance with the internal wave attractors investigated in sloshing tanks (see Maas et al. *Nature* 1997). Next to DNS numerical simulations, experiments are conducted in air with $Pr = 0.7$ and in water-glycerin mixtures with $Pr = 2$ to 7, in a rectangular cavity of which the height is varied. Circulation patterns and waves are measured using the T-LIF fluorescein-temperature method and PIV.

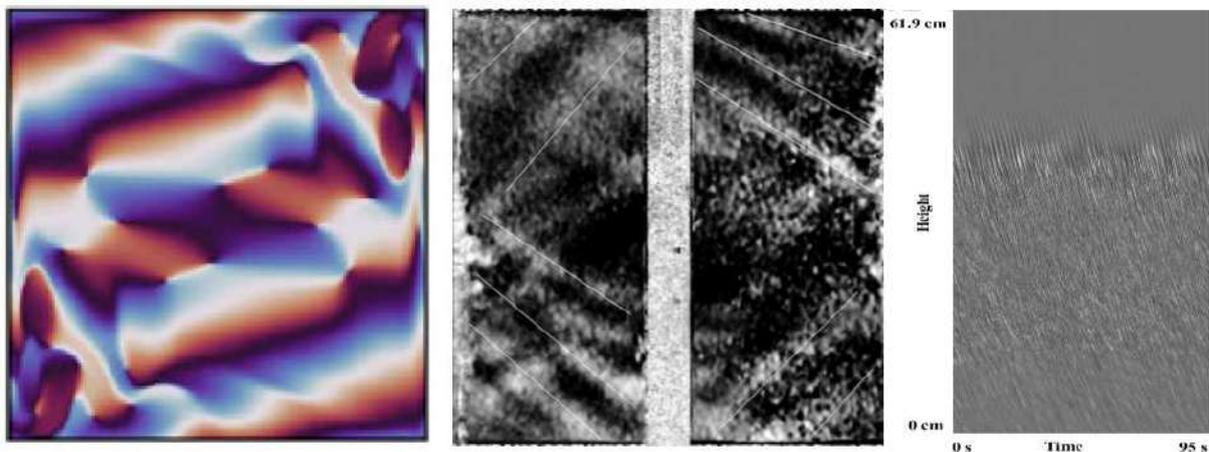


Figure 1: (a) Phase map at $Pr = 0.71$ showing the wave pattern in the 2D wave regime at the onset of instability (Khoubani et al, *J. Fluid Mech.* 2024), and (b) shadowgraph picture of wave pattern in 3D for $Ra \approx 10^{11}$ (the bar in the centre holds the thermistors), and (c) Space time diagram of the internal waves generated near the wall (interim report of WJH Berghuis, 2016).

Rossby waves over rough bathymetry

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Topography plays a central role in ocean dynamics, but our intuition is often based on flat bottom models. This includes aspects like the baroclinic modes used for representing vertical structure and for baroclinic instability. A good example is Rossby waves, whose vertical structure and stability are both affected by bathymetry. Relatively modest topography causes the waves to be surface-trapped, which in turn alters their deformation radius and propagation speed. Rossby waves are also baroclinically unstable, and this is altered by bathymetry as well. If the topography is steep enough, energy is transferred directly to topographically-locked flows, rather than to the most unstable wave found over a flat bottom. The critical height can be deduced by scaling and the instability condition can be rationalized via a simple wave triad calculation. The instability may be important for the overall energy balance of the ocean, with regards to the transfer of energy from surface-intensified mesoscale eddies to the bottom where it is dissipated.

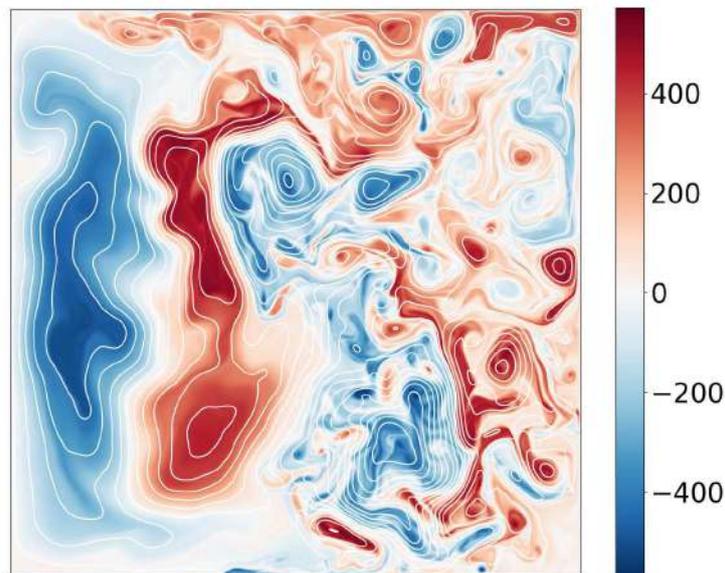


Figure 1: Instability of a Rossby wave over rough bathymetry. The basin is $\sqrt{500}$ times larger than the surface deformation radius. The plot shows contours of the surface streamfunction, ψ_1 , over color contours of the surface potential vorticity, q_1 .

Vertical velocities in laboratory surface vortices

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Fine-scale oceanic structures, such as vortices and fronts, escape the classical two-dimensional geostrophic description and exhibit ageostrophic vertical motions. Measurements and understanding of these fine-scale vertical velocities are one of the main open questions among the oceanography community, as they participate to ocean mixing or other transport of diverse quantities.

Geophysicists have derived the ω -Equation¹ to diagnose these vertical velocities from their horizontal data. Assuming a flow is quasigeostrophic and divergence free, this equation states that vertical velocities will arise in order to compensate the loss of geostrophic balance and to conserve potential vorticity along streamlines. However, the difficulty to measure velocity and scalar fields at sea on horizontal extended domains make the use of this equation challenging². The ω -Equation reads:

$$N^2 \nabla_h^2 \mathbf{w} + f^2 \frac{\partial^2 \mathbf{w}}{\partial z^2} = 2 \frac{g}{\rho_0} \nabla_h \cdot (\nabla_h \vec{u}_g \cdot \nabla_h \rho) \quad (1)$$

with \mathbf{w} the ageostrophic vertical velocity, \vec{u}_g the geostrophic horizontal velocity field, ρ the density, f the Coriolis frequency, N the Brunt-Väisälä frequency and ∇_h the horizontal gradients.

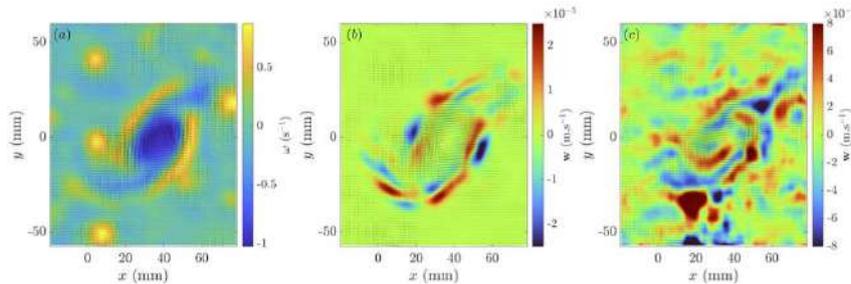


Figure 1: (a) Vorticity map of our elliptical floating vortices obtained from PIV measurements. $Re = 300$, $Ro = -0.2$. (b) Resulting \mathbf{w} ($\text{m}\cdot\text{s}^{-1}$) field obtained from the ω -Equation model (equation 1). (c) Resulting \mathbf{w} ($\text{m}\cdot\text{s}^{-1}$) field obtained from integrated horizontal divergence of \vec{u}_g .

To our knowledge, the predictions of the ω -Equation have only been satisfactorily compared to a numerically simulated oceanic vortex³. In the present study, we test the predictions of the ω -Equation against laboratory experiments with direct measurements of vertical velocity \mathbf{w} . Using a rotating table and density stratification, we investigate non-axisymmetric surface vortices⁴ (Figure 1 a). As shown in Figure 1 b, the predicted vertical velocities calculated from the ω -Equation are relatively small ($\simeq \pm 20 \mu\text{m}\cdot\text{s}^{-1}$) and primarily appear at the vortex edges, where the vorticity sign changes, acting to restore flow stratification. However, our measurements of \mathbf{w} obtained from horizontal divergence (Figure 1 c) are five times larger. This discrepancy is further confirmed by direct particle tracking measurements, which indicate a magnitude of approximately $\pm 100 \mu\text{m}\cdot\text{s}^{-1}$ for \mathbf{w} . To address this inconsistency, we are currently incorporating dissipative terms into the ω -Equation to assess the role of viscous diffusion in enhancing internal recirculation in the vortex and thus vertical velocity magnitude⁵. These results are further completed through the use of theoretical models of oceanic vortices, with the aim of helping oceanographers in quantifying regions of upwelling and downwelling in the ocean.

¹Hoskins et al., *Quarterly Journal of the Royal Meteorological Society* **104** (1978).

²C. Comby, *PhD Manuscript*, **2023AIXM0408** (2023).

³A. Viudez, D. Dritschel, *Journal of Fluid Mechanics* **483** (2003).

⁴De La Rosa Zambrano et al., *European Journal of Mechanics-B/Fluids* **61** (2017).

⁵G. Facchini, M. Le Bars, *Journal of Fluid Mechanics* **804** (2016).

Topography-generated submesoscale coherent vortices near the mid-Atlantic ridge

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Submesoscale coherent vortices (SCVs), although not resolved in climate models, can be long-lived structures affecting the global distribution of heat and other tracers¹. SCVs are commonly generated by slope boundary current separation, where the subsequent instability of vorticity filaments leads to the formation of coherent structures². Although this process can be symmetrical, most of the observed SCVs are anticyclonic. Here, in the first part of this PhD, we use a high-resolution numerical simulation (GIGATL1) and an eddy tracking algorithm based on the Okubo-Weiss parameter. We study the SCV population close to the Mid Atlantic Ridge (MAR) on the 27.8 isopycnal surface (2000-2500m depth). Our region of focus is located close to the Equator (Figure 1.a), where the local Coriolis frequency is relatively small, which may have great influence on the local dynamics. We study the statistics of the population of SCVs, namely their intensity, size, lifespan, polarity, propagation speed, and direction. Our first results indicate that cyclonic SCVs are more numerous than their anticyclonic counterparts and can be equally long-lived (hundreds of days at most), although the largest SCVs are mostly anticyclonic (Figure 1.b and c). A method based on the potential vorticity (PV) anomaly is proposed to estimate the vertical to horizontal aspect ratio (H/L) of vortices and carry out a comparison with the proposed scalings in the literature³. Future studies will focus on various observed features such as PV sign reversal for anticyclones, vertical alignment of vortices, interactions with the topography, and influence of the low Coriolis frequency, in the vicinity of the Equator. A similar study could also be performed at basin scale, for the whole Atlantic Ocean or in regions with different characteristics (at mid-latitude or away from the MAR).

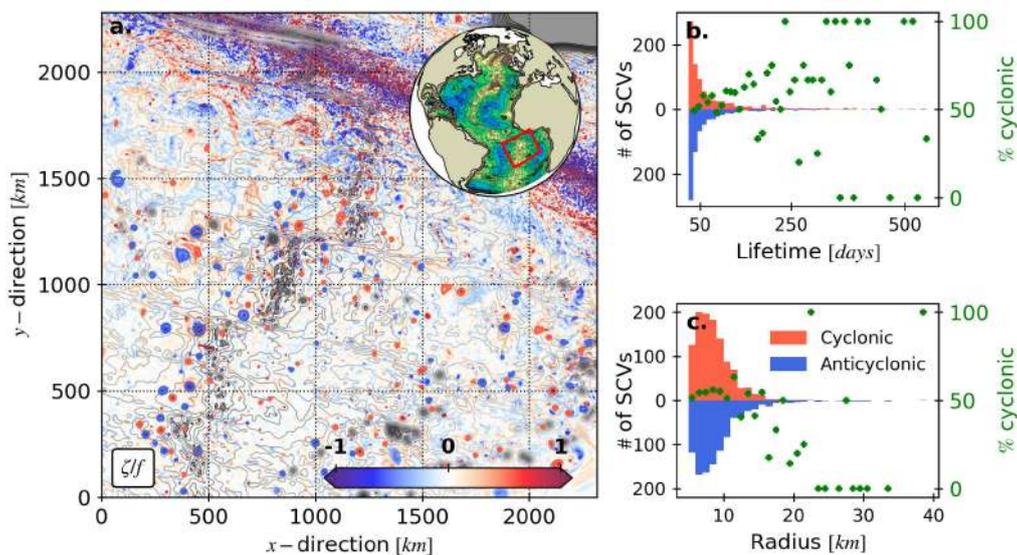


Figure 1: **a.** Snapshot of relative vorticity normalised by the Coriolis frequency ζ/f on the 27.8 isopycnal surface, contours of the detected anticyclonic (cyclonic) vortices are indicated in blue (red), and 250m level-step isobaths in grey. Distribution of vortices as a function of **b.** lifespan and **c.** radius. The percentage of cyclonic vortices for each bin is indicated by green markers.

¹ McWilliams, *Royal Society* **472** (2016) ² Srinivasan et al., *Journal of Physical Oceanography* **49**, 1949–1971 (2019)

³ Hassanzadeh et al., *Journal of Fluid Mechanics* **706**, 46-57 (2012)

The role of equatorial waves in spontaneous emission

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¹ *MIDS, KU Eichstätt–Ingolstadt, Germany*

We perform an experimental study to quantify the emission of inertia gravity waves in rotating shallow water flow on the sphere. Contrary to the situation on the f -plane, the full dispersion relation does not have a spectral gap, as equatorial Kelvin and mixed Rossby-gravity waves fill the frequency gap between Rossby and inertial-gravity modes. Employing the TIGAR model in a one-layer configuration and using optimal balance as an accurate diagnostics, we are able to quantify the transfer of energy between the different compartments and compare the dynamics with and without interactions involving equatorial waves. We confirm that it is indeed the equatorial waves that are responsible for fast energy transfer from Rossby to inertia-gravity waves, to the extent that this transfer is asymptotically independent of the rotation rate.

Steady baroclinic vortices radiating Rossby waves in vertically sheared flows

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A quasigeostrophic zonal flow with vertical shear is linearly stable if the potential vorticity everywhere increases with latitude. The reason is that the pseudomomentum is negative definite. Thus, because of zonal momentum conservation, Rossby waves are unable to extract energy from the background flow. However, a coherent vortex with trapped fluid can take up momentum by drifting in the meridional direction. This can compensate for the momentum carried away by Rossby lee waves excited by the vortex. The result is that the vortex can act as a catalyst, extracting energy from the background flow and emitting it as Rossby waves.

This idea is supported by studying a baroclinic vortex embedded in a vertical shear flow in a two-layer quasigeostrophic model on the beta-plane. The background PV is uniform in the upper layer, so that the flow is marginally stable. The background flow vanishes in the lower layer and is eastward in the upper layer, so that the beta-effect there is compensated by the potential vorticity (PV) gradient associated with the meridional slope of the layer interface. An explicit steady solution is found that describes a vortex generating Rossby lee waves. The wave generation induces a meridional drift, to conserve zonal momentum. Since the PV is conserved in the trapped fluid in the upper layer, the vortex amplitude does not decrease, although energy is required to generate the Rossby waves. The solution is confirmed by numerical simulations.

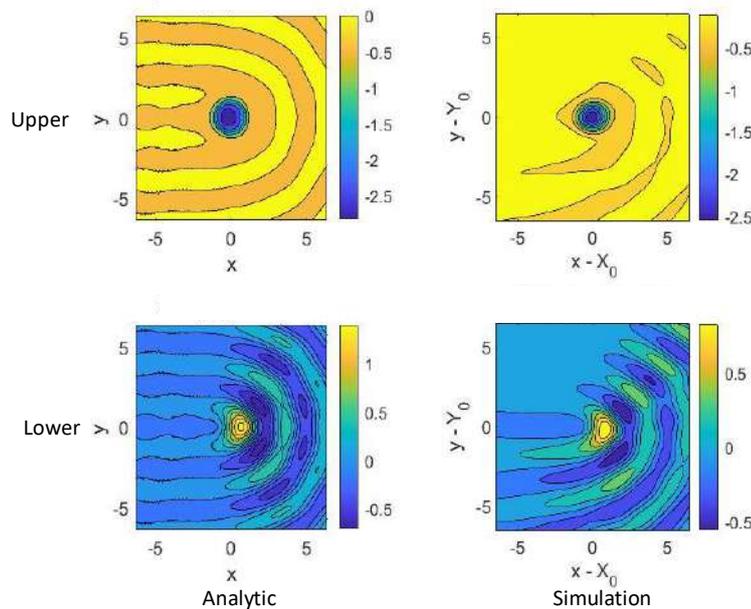


Figure 1: Streamfunction in the upper and lower layer of a vortex that continuously generates Rossby waves, and yet is stationary. The analytic steady solution was used as initial condition in a simulation, and the figure shows the analytic solution and the simulation after a long time.

Relationship between mesoscale eddy surface temperature anomaly and its vertical structure : case study in the Arabian Sea

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Mesoscale anticyclonic (respectively cyclonic) eddies in the ocean were considered as inducing predominantly warm (cold) eddy sea surface temperature anomalies (ESSTA). Progresses in eddy automatic detections algorithms over the last decade strongly tempered this assessment, with a significant proportion of "inverse" ESSTA, which are anticyclonic cold and cyclonic warm surface signatures and account between 15 and 30% of observations globally. Inverse ESSTA are assumed to be the signature of subsurface eddies, defined as mesoscale structure with density anomalies of opposite sign at depth and at the surface¹. This relationship is confirmed in the global ocean on average², but does not explain the marked ESSTA seasonality³ nor ensure its validity for a single ESSTA observation.

The Arabian Sea is an interesting basin to study mesoscale signatures because of the strong interactions between eddies, coastal upwelling and monsoon winds. Using a state-of-the-art altimetric eddy tracking from 2000 to 2015, we show that ESSTA vary strongly in time and space. Inverse ESSTA proportion is linked to large scale mixed layer depth, decreasing while mixed layer deepens. Due monsoon wind patterns, two inverse ESSTA maxima are observed in the Central Arabian Sea in spring and fall, but only one summer maxima is observed in the Northern part.

Using colocated in situ vertical profile, we define an eddy significative depth based on its density anomaly. A linear relationship is found for anticyclones, anticyclones colder by about 0.3°C being about 100m deeper. This relationship holds only near the Omani coast, where deep structures are observed. An anticyclone/cyclone asymmetry appears as cyclonic ESSTA tends to be shallower and to correlate more with the mixed layer.

Eddy temporal tracking revealed that ESSTA magnitude can be significantly impacted by background effects, such as interactions with thermal fronts or cold upwelling. Therefore the ESSTA appears as a useful but complex marker of mesoscale evolution and vertical structure. It should be analysed along a mesoscale tracking rather than as a binary snapshot indicator of surface versus subsurface eddy.

¹Assassi et al., *Journal of Physical Oceanography*, **46**(8), 2529–2552 (2016)

²Ni et al., *Journal of Physical Oceanography*, **51**(9), 2793–2806 (2021)

³Moschos et al., *Remote Sensing*, **14**(15), 3807.(2022)

An interaction mechanism sustaining near-equilibrium shielded geophysical vortices

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¹ Universitat Politècnica de Catalunya, Spain, ² University of St Andrews, UK, ³ Institut de Ciències del Mar (ICM-CSIC), Spain

We investigate the interaction between two equally-signed neutral vortices, namely vortices with a vanishing area integral of vorticity in inviscid isochoric two-dimensional (2D) flows or a vanishing volume integral of potential vorticity anomaly in three-dimensional (3D) quasi-geostrophic (QG) flows. The vortices have a continuous (potential) vorticity distribution, and are linear combinations of appropriately normalized cylindrical (or spherical) Bessel functions of order 0, truncated at a zero of the Bessel function of order 1. Some pairs of neutral vortices reach an oscillating near-equilibrium state, attracting and repelling each other as a result of the exchange of small amounts of vorticity in their peripheries (figure 1). This vorticity exchange generates a dipolar moment within each vortex which separates the vortices slightly, whereas the subsequent radial redistribution of the vorticity causes the vortices to come back closer again. The interaction is slower and weaker in 3D QG flows, as the potential vorticity exchange primarily takes place close to the horizontal mid-plane of the vortices. These results have been corroborated using two radically different numerical models, namely a pseudo-spectral model and a high-resolution contour advection model, both in 2D and in 3D.

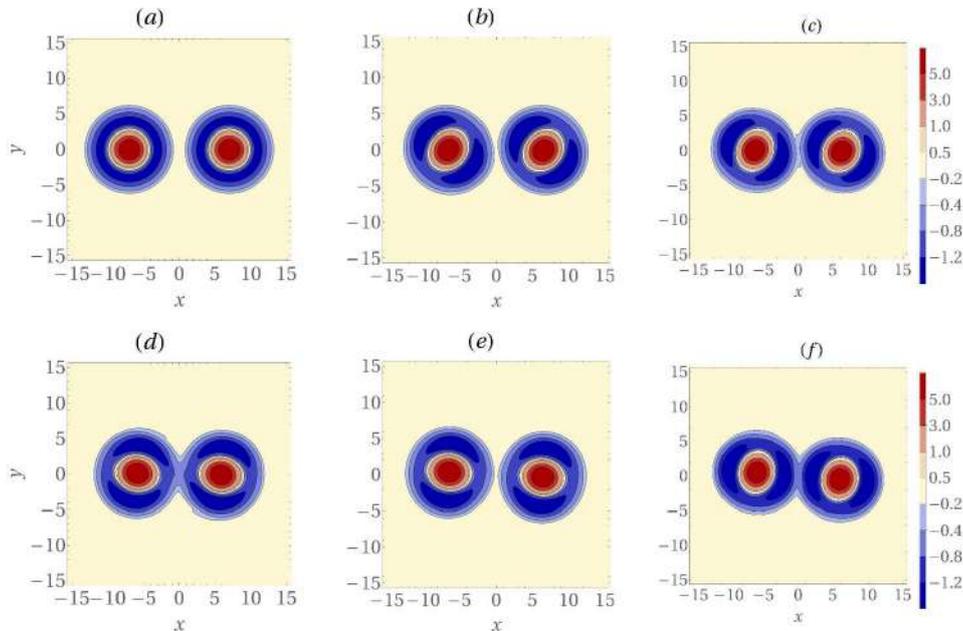


Figure 1: Vorticity field $\zeta \times 10$ of two initially touching neutral vortices $\zeta_{1,-1}$ at times (a) $t = 0$, (b) $t = 2190$, (c) $t = 2580$, (d) $t = 3000$, (e) $t = 4610$ and (f) $t = 5650$, using the 2D pseudo-spectral code.

Baroclinic instability in the coupled atmosphere ocean dynamics

X Carton, A Vic, J Gula

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We study the linear instability of baroclinic parallel flows in two superimposed fluids. These flows are westerly jets in each fluid. They are thermally or mechanically coupled. The fluids are stably stratified, internally and mutually (the upper fluid is lighter than the lower fluid). For each fluid, we use the two-level surface quasi-geostrophic dynamics. Each jet is perturbed with normal modes.

Firstly, we check that, in the uncoupled case, the classical results of the Eady baroclinic instability are recovered. Then, in the case where the fluids are thermally and/or mechanically coupled, we investigate how the original instability is modified by this coupling. The four equations for linear instability are solved numerically via a matrix method.

With thermal coupling, and for meridionally uniform perturbations, a new mode of instability appears for long waves. This pair of unstable modes converges towards the modes of the uncoupled fluids at medium wavelengths. For perturbations with a non trivial meridional structure, the thermal coupling essentially damps the instability. For an upper flow with a larger deformation radius than in the lower flow, the growth rates of the perturbation are therefore more strongly altered in the former than in the latter. With mechanical coupling, the instability is essentially damped at large to medium scales, while the short-wave cut-off is extended towards smaller waves. When the fluids are both thermally and mechanically coupled, these effects add up.

The results found in the numerical model are confirmed by an idealized model of amplitudes and phases of perturbations for which simple solutions exist.

Finally, we have run a nonlinear 4 level SQG model (two levels for the atmosphere and for the ocean, respectively) - either with purely turbulent initial conditions and an unforced evolution, or forced by the vertical shear of horizontal velocity (and by the meridional buoyancy gradient) in each fluid and initialized by a white noise of weak amplitude. We vary each fluid parameters (thickness, vertical shear of velocity) and the coupling. We analyze the various outcomes of these simulations.

A Rapidly Rotating Baroclinic System: Insights into Large-Scale Structures in Astrophysical Systems

Shan-Shan Ding, Bob Watkins and Peter Read

University of Oxford, UK

Heat, momentum, and energy transfer play a fundamental role in shaping large-scale structures in geophysical and astrophysical systems. We have constructed a high-speed rotating platform (capable of rotation speeds up to 10 Hz) in the laboratory to study the dynamics of large-scale convective fluid structures in an annular cavity. The cavity has dimensions of 0.53 m outer diameter, 0.2 m inner diameter, and 0.41 m height and is enclosed by a heated (chilled) copper outer (inner) cylinder with a thermally insulated flat bottom. To measure velocity fields and total heat transfer simultaneously, we integrate multiple-level laser sheets into the inner cylinder and use a ceiling-mounted camera synchronized with the rotating tank for conducting image acquisition for particle image velocimetry. We plan to explore two configurations of top surface: a free-top surface, where a sharply curved, centrifugally deformed interface induces a strong topographic beta effect, potentially allowing access to zonostrophic turbulent regimes characterized by multiple alternating zonal jet flow; a solid top surface, where radial centrifugal acceleration (g_c) dominates over vertical gravitational acceleration (g) (with g_c/g reaching ~ 100 in the limits of 10 Hz rotation speed), leading to a transition from baroclinic instability to radial convection. Our studies aim to measure total heat flux, angular momentum, and energy transfer both spatially and between different scales across a wide parameter range. The results are intended to provide valuable insights into the mechanisms driving large-scale zonal flows, accretion disk formation, and planetary atmospheric dynamics as well as on flows in rapidly rotating machinery.

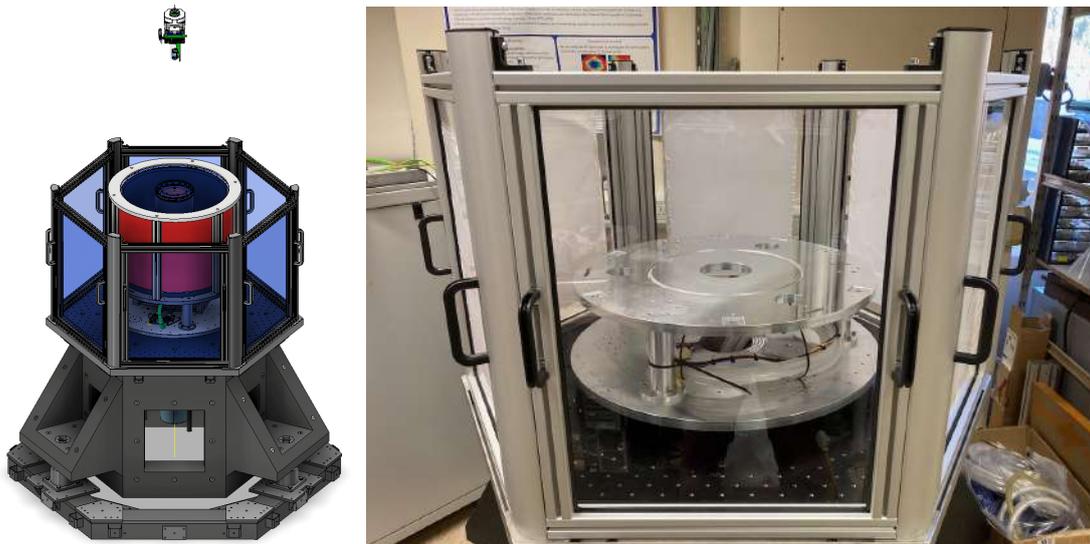


Figure 1: [Left] Schematic plot of the experimental setup and [right] photograph of the rotating table.

Geometric internal wave focusing: from weak to strong viscous effects

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The focusing of the internal waves generated by a horizontally oscillating torus in a linearly stratified fluid is studied experimentally over a wide range of Stokes numbers St , where $St = \omega a^2 / \nu$ (with ω the oscillation frequency, a the minor radius of the torus, and ν the kinematic viscosity) quantifies viscous effects. St is varied by using different torus sizes. Earlier results showed that for large Stokes numbers, the energy distribution across higher harmonics and the fundamental wave, as well as the wave dissipation and breaking, change significantly. For small oscillation amplitudes, the results align well with linear viscous theory.

To study the mean flow, the Stokes drift is calculated from the linear analytical expression of the internal waves and compared with the experimental results for different Stokes numbers. For moderate St good agreement is found between the theoretical and experimental Stokes drift which opposes the mean flow in the focal region and close to the torus.

In the linear approximation, the amplitude of oscillation is infinitely small compared to the size of the object. When the amplitude of oscillation becomes finite, however, higher harmonics are generated. In the present experiments, this parameter is varied and shows variations in harmonics generation.

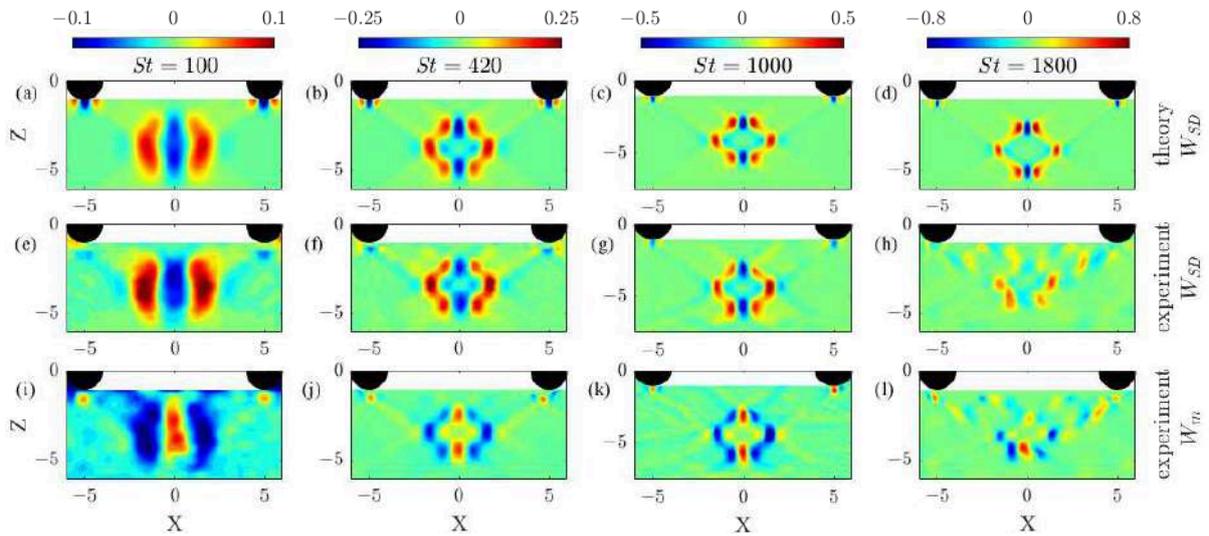


Figure 1: Vertical drift velocity W_{SD} calculated (a–d) theoretically and (e–h) experimentally, and (i–l) vertical mean velocity W_m measured experimentally at $Ke = A/a = 0.25$ with A the oscillation amplitude, for the small torus (minor radius $a = 2$ cm and major radius $b = 10$ cm) (a,e,i), the medium-torus ($a = 4$ cm and $b = 20$ cm) (b,f,j), the large torus ($a = 6$ cm and $b = 20$ cm) (c,g,k), and the extra large-torus ($a = 8$ cm and $b = 40$ cm) (d,h,l).

Vortex disruption in quasigeostrophic shallow-water MHD

Luke Gostelow^{1,2}, Stephen Griffiths², and David Hughes²

¹ *University of Glasgow*, ² *University of Leeds*,

When Spiegel and Zahn¹ first proposed that anisotropic turbulence could explain the radial thinness of the solar tachocline, they also suggested shear flow instability as its natural cause, driven by the differential rotation in the convection zone. However, in hydrodynamic systems, shear flows typically produce large-scale vortices, such as those observed on Earth and Jupiter. An additional ingredient in the Sun is the magnetic field, and even if its strength in the tachocline is small relative to that observed on the surface, vortices can amplify an ambient field by flux expulsion by several orders of magnitude (proportional to the cube root of the magnetic Reynolds number). Magnetic hoop stresses can then disrupt the vortices and drive the flow to smaller scales.

In this study, we investigate the role of rotation and stratification in vortex disruption using a quasigeostrophic shallow-water model. We demonstrate how these factors influence the evolution of vortex disruption both directly through their effect on the vortex's dynamics and indirectly by shaping the initial state of the vortex emerging from shear instability.

¹Spiegel & Zahn, *Astron. Astrophys.* **265**, 106–114 (1992)

Impact of Deep Thermal Forcing on Jupiter’s Baroclinic Instability and Jet Dynamics

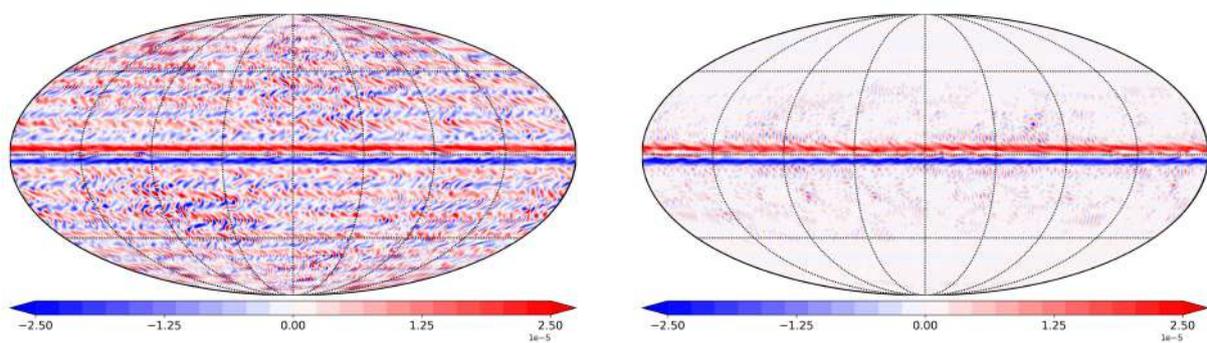
Xinmiao Hu¹, Peter Read¹, Roland Young² and Greg Colyer¹

¹ University of Oxford, UK, ² University of Aberdeen, UK,

Numerical simulations and analysis of observations have suggested that the structure of Jupiter’s jets are strongly influenced by baroclinic instability¹, which could be shaped by the planet’s atmospheric thermal structure. Unlike Earth, where the thermal structure is primarily driven by solar heating, Jupiter has a substantial intrinsic heat flux. Previous modelling studies² have shown the effect of changing (uniform) interior heat flux on baroclinicity and super-rotation. Yet, the effect of non-uniform heat flux has been unexplored.

In this study, we introduced latitudinal variations in interior heat flux at the lower boundary of a Jupiter numerical global circulation model (GCM)³ that has generated alternating, eddy-driven, Jupiter-like midlatitude jets through baroclinic instability. With this model, we run several simulations with different latitudinal gradients in interior heat flux. Variations in the bottom thermal boundary condition significantly alter the atmospheric dynamics, as illustrated in Fig. 1. The mid-latitude jets are altered in terms of their strength, width and migration speed. Our preliminary results show that the latitudinal varying heat flux changes the temperature structure, which then modifies the strength of baroclinic instability.

We present the analysis of energy conversion rate, Eady growth rate and eddy-mean flow interactions to demonstrate how these changes drive changes in zonal jets. We also discuss the implications on the bottom thermal boundary condition of Jovian weather-layer GCMs and for jet formation on other giant planets.



(a) Relative vorticity (s^{-1}), run with lowest flux gradient. (b) Relative vorticity (s^{-1}), run with highest flux gradient.

Figure 1: Mollweide projection of the relative vorticity at 1 bar at the end of two simulations.

¹Read et al. *Geoscience Letters* **7**, 10 (2020)

²Liu and Schneider *Journal of Atmospheric Sciences* **68**, 2742-2756 (2011)

³Young et al. *Icarus* **326**, 253-268 (2019)

Orientation dynamics of an ice crystal in cloud

Himanshu Mishra^{*}, Pijush Patra[†], and Anubhab Roy^{*}

We investigate the orientation dynamics of an ice crystal in homogeneous isotropic turbulence and in the presence of an external electric field. At the scale of the ice crystal, we assume that viscous effects dominate the flow, and thus, the dynamics can be studied in the Stokesian regime. Further, when the size of the ice crystal is smaller than the Kolmogorov scale, the flow field around the particle can be modeled locally as a stochastic linear flow. This approximation becomes particularly useful when studying the orientation dynamics of ice crystal in homogeneous isotropic turbulence and when the orientation dynamics of the ice crystal is governed by the Jeffery equation¹, which involves the local fluctuating velocity gradient. The turbulent velocity gradient is obtained from the stochastic model given by the Girimaji and Pope². The model uses the log-normal distribution of the pseudo-dissipation rate. In the presence of an external electric field, the ice crystal aligns in the direction of the electric field. We study the competition due to the torque induced by the turbulent velocity gradient and the electric field. The orientation dynamics is analyzed by varying a non-dimensional parameter Σ , which is defined as a ratio of the Kolmogorov time scale and the electric relaxation time scale. For lower values of Σ , we show that the ice crystal exhibits an isotropic orientational distribution, whereas it fluctuates along the direction of the electric field at higher values of Σ . We calculate moments of the orientation distribution at large electric field limits using asymptotic methods and compare them with numerical calculations. A second-order moment in the orientation, which quantifies the fluctuations in the orientation, depends on Σ and the shape of an ice crystal. The fourth-order moment of the orientation, a measure of the non-Gaussian statistics of the orientation distribution, increases from its Gaussian value with the increase in Taylor-scale Reynolds number.

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[†]Nordita, KTH Royal Institute of Technology and Stockholm University, Hannes Alvéns väg 12, 23, SE-106 91 Stockholm, Sweden

¹Jeffery, *Proc. R. Soc. London, A.* **102**, 161-179 (1922).

²Girimaji and Pope, *Phys. Fluids* **2**, 242-256 (1990).

Thermal Image Velocimetry for experimental rotating fluid dynamics

Rémy Monville¹, Daphné Lemasquier², Cy David¹, Céline Guervilly³ and Jonathan Aurnou¹

¹University of California Los Angeles, USA ²University of St Andrews, UK ³Newcastle University, UK

In experimental fluid dynamics, one challenging aspect is the measurement of fluid velocity. Besides one-dimensional Doppler measurements, the only way to obtain a two-dimensional velocity field is by tracking features within the flow. The most prevalent method for measuring fluid velocity in the laboratory is Particle Image Velocimetry (PIV), which uses the tracking of neutrally-buoyant particles. PIV relies on a laser sheet to illuminate the particles in a plane and requires the fluid to be transparent to visible light. It then becomes challenging to use PIV in certain geometries, for instance when one aims to measure velocity on a curved surface instead of a plane. Here, as an alternative to PIV, we investigate how measurements of the temperature at the free surface of a fluid could be used to retrieve velocity fields. We focus on a free-surface convective flow, where the surface temperature field can be measured very precisely using an Infrared Camera. Under the assumption that the temperature field is mainly advected by the flow, our hypothesis is that tracking thermal structures can allow to derive velocity fields, a method we call "Thermal Image Velocimetry" (TIV). We employ a dense optical flow method "OpenOpticalFlow"¹ to track the temperature field's structure. This method has already proven its effectiveness in tracking clouds in planetary atmospheres, as demonstrated in the measurements of Jupiter's cloud layer². We present here a benchmark study using the "Coreaboloid" experimental setup³, which includes infrared measurements of the free surface and PIV measurements on a horizontal plane. Additionally, we also use synthetic data from quasi-geostrophic simulations, reproducing the experiment. We investigate how TIV can be used to meet specific constraints in the measurement of rotating convective experimental flows. We obtain a velocity field of quality comparable to PIV. These promising results encourage further application, including to measure velocity fields at the surface of a shallow paraboloid fluid layer.

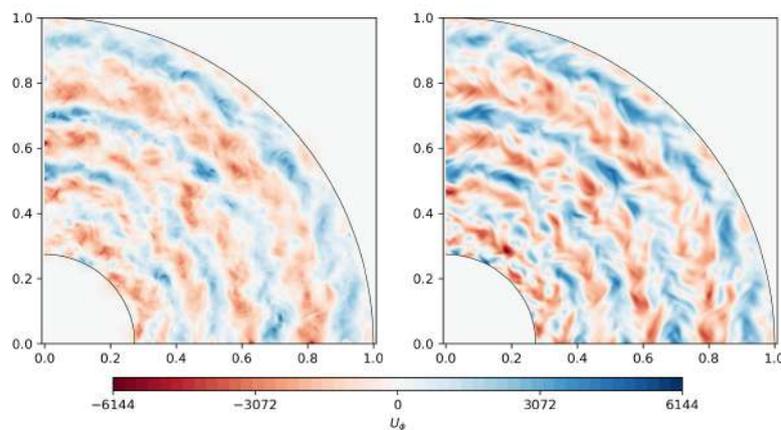


Figure 1: Comparison between inverted (left) and simulated (right) velocity field, from quasi-geostrophic simulation of rotating convective flow. Zonal jets are emerging due to the instability caused by the temperature gradient between the inner and outer cylinders, as well as the rotation and β -effect.

¹Liu, T., *Journal of Open Research Software* **5**, 29 (2017)

²Liu, T., & Salazar, D. M., *Experiments in Fluids* **63**, 76 (2022)

³Lonner et al., *JGR Planets* **127**, e2022JE007356 (2022)

Unveiling a Novel Particle-Induced Instability in Shear Flows

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¹ Indian Institute of Technology Madras, India, ² Arizona State University, USA

We investigate the instability of a shear flow laden with non-uniformly distributed dust particles¹. Although each component is stable on its own—a simple shear flow is stable to infinitesimal perturbations, and a stationary dust band remains unaffected without a background flow—we demonstrate here that their interaction can trigger destabilisation through two-way coupling. This instability arises purely from the momentum feedback of the particle phase on the fluid, significantly modifying the flow dynamics. Using Eulerian-Lagrangian simulations, we illustrate the emergence and evolution of this novel instability by comparing cases with and without two-way coupling. Figure 1 presents the simulation results, showing the evolution of vorticity disturbances. In the one-way coupled case, disturbances decay over time, whereas in the two-way coupled case, they grow, demonstrating the destabilising effect of particle feedback.

We conduct a linear stability analysis using an Eulerian-Eulerian formulation to gain further insight into the instability mechanism. The results confirm that the instability is inviscid in nature and is characterised by a critical wavelength below which perturbations do not grow. This threshold is determined by the size of the particle band, highlighting the crucial role of preferential concentration in triggering the instability. Our findings provide new perspectives on the dynamics of particle-laden shear flows, revealing how momentum feedback from particles can generate and sustain flow instabilities even in otherwise stable shear profiles.

These results have broader implications for geophysical and astrophysical fluid dynamics, where particle-fluid interactions play a crucial role. In particular, they help us understand how shear-driven instabilities develop in particle-laden systems like sea spray dynamics in the ocean-atmosphere boundary layer and dust-laden flows in protoplanetary disks under Keplerian shear. Understanding such instabilities is key to improving models of particulate transport and turbulence in planetary and astrophysical environments.

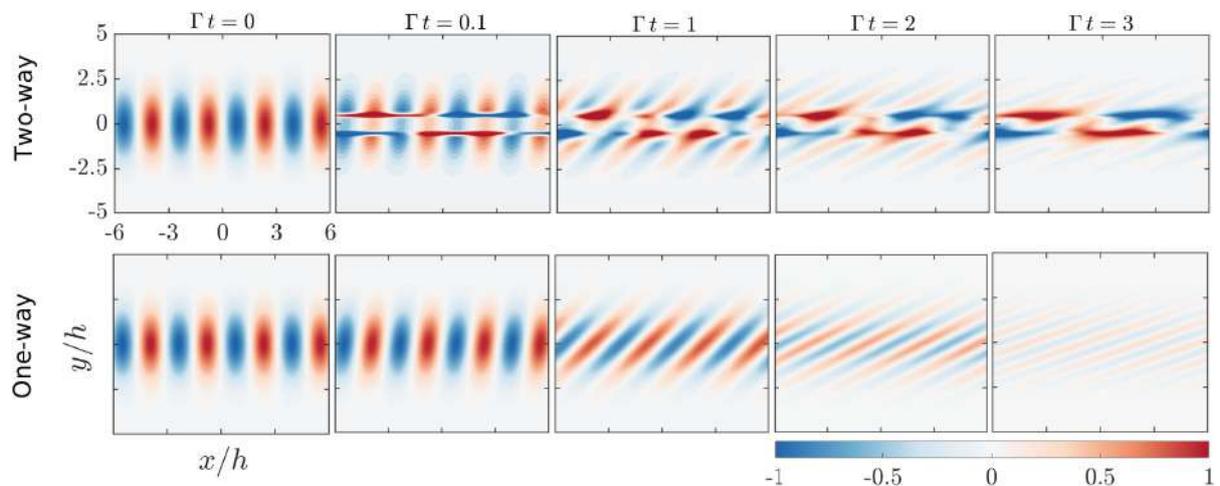


Figure 1: Time evolution of vorticity disturbances in one-way and two-way coupled Eulerian-Lagrangian simulations.

¹Nath et al., *JFM* **1002**, A17 (2025)

Analytical study of instabilities in idealized shielded vortices

Raphaël Ravasse¹, Xavier Carton¹ and Jonathan Gula¹

¹ Université de Bretagne Occidentale, France,

We study the stability of ringed Rankine vortices. They consist of a circular core with a piecewise constant vorticity profile and two concentric annuli, also with piecewise constant vorticity. The core and outer annulus have the same sign of vorticity; the central annulus has either zero or opposite sign vorticity. This choice is based on wind observations at the poles of gas giant planets. We assess the barotropic (horizontal shear) instability of these eddies. We determine the most unstable azimuthal modes (in the normal mode theory) and their growth rates. Time permitting, singular modes will be studied. We then numerically model the nonlinear evolution of these unstable vortices. We compare these evolutions with the predictions of the linear analysis, and a Fourier analysis of the perturbation is used to explain possible differences.

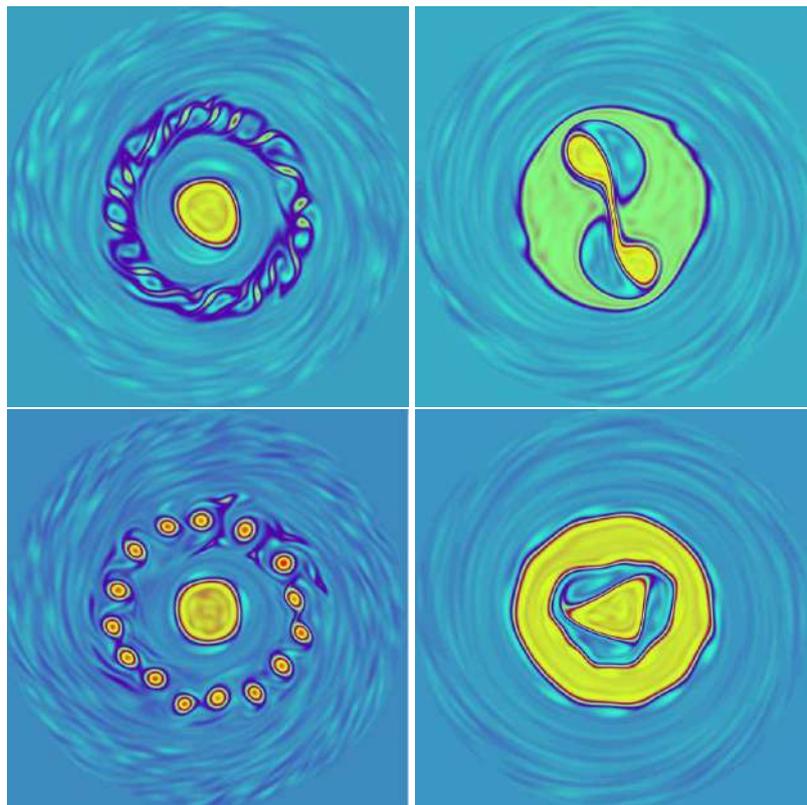


Figure 1: instability of vortices with different values of shielded vorticity and radii ratios

Bistable Ocean Circulation Beneath Antarctic Ice Shelves: Insights from idealized numerical simulations

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² *CNRS, ENS de Lyon, LPENSL, UMR5672, 69342, Lyon cedex 07, France*

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The circulation beneath Antarctic ice shelves plays a crucial role in modulating ice sheet mass loss and influencing deep ocean water formation. Recent low-dimensional models have shown evidence of a bistable behavior of subglacial seas, resulting from the competition between basal meltwater discharge and brine rejection from sea ice formation. Using numerical simulations with the NEMO general circulation model, we test the bistability hypothesis in an idealized set-up of ice-shelf ocean cavity and investigate the key underlying dynamical processes.

On the one hand, we show the existence of a warm mode allowing warm deep waters to fill the cavity, increasing basal melt and producing a strong meltwater plume on the western edge of the cavity. Circulation at the front of the ice shelf is cyclonic. On the other hand, there is a cold mode with cold surface waters plunging and filling the cavity when brine rejection at the ice-shelf front is high. The meltwater plume weakens and the circulation becomes anticyclonic at the front of the ice shelf. We demonstrate that the transition between the warm and cold modes is abrupt and non-reversible, and we discuss the impact of modeling choices on the cavity dynamics.

We show that oscillatory motions inside the ice-shelf cavity strongly modulate the local melt rates and are reminiscent of topographic Rossby waves. Thus, our work highlights the importance of mesoscale motions and sub-inertial waves in controlling the melt rate and tipping behavior of subglacial seas.

Variants of the Plumb-McEwan Laboratory Analogue of the Quasi-Biennial Oscillation, and Efforts to Simulate it Numerically

Sol Sanders-Farmer^{1,2}, Alfonso Castrejon-Pita², Scott Osprey¹ and Peter Read¹

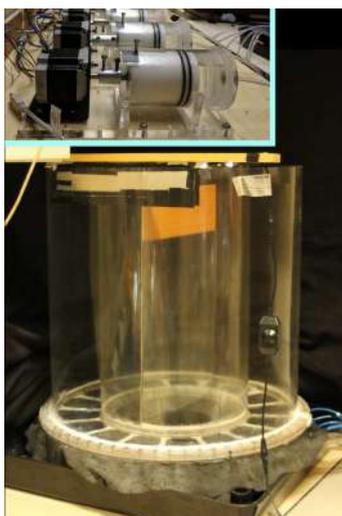
¹ Department of Atmospheric, Oceanic, and Planetary Physics, University of Oxford, UK

² Department of Engineering Science, University of Oxford, UK

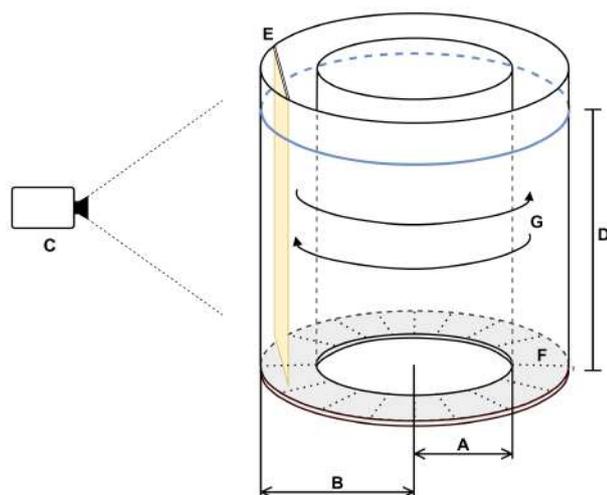
The Quasi-Biennial Oscillation (QBO) is the dominant feature of equatorial stratospheric circulation, driven by wave-mean flow interactions. Despite its theoretical understanding, reproducing the QBO in global climate models (GCMs) remains challenging due to unresolved wave dynamics and parametrization uncertainties. This study explores a complementary investigative approach using the laboratory analogue first pioneered by Plumb and McEwan¹ as well as numerical simulations to investigate QBO-like oscillations in a controlled setting.

A cylindrical annulus filled with salt-stratified water is forced by independently controlled pistons to generate internal gravity waves, mimicking the QBO's wave-driven dynamics (Fig. 1). Preliminary results demonstrate the generation of mean flows and descending shear zones, consistent with theoretical predictions and previous studies such as by Semin et al.² Using independently programmable forcing pistons we look to present initial results under more complex wave-forcing.

Concurrently, the Met-Office Rotating Annulus Laboratory Simulation (MORALS) is adapted to numerically simulate the apparatus, replicating key wave-mean flow processes but encountering challenges in realistic phase switching. Analysis of the numerical apparatus is presented demonstrating the potential and limitations of the relatively simple numerical approach.



(a) Photographs of the apparatus. Insert: Stepper motors and pistons. Main: Empty annulus.



(b) Diagram of the tank. [a] Inner radius, [b] Outer radius, [c] Camera, [d] Depth of stratified water, [e] LED sheet, [f] Inflatable membrane [g] Mean-flow

Figure 1: The experimental apparatus used for our investigation

¹Plumb R, McEwan, A., *J. Atmos. Sci.* **35**, 1827-1839 (1978)

²Semin B, Pétreils F., *Comptes Rendus. Physique* **25**, 1-25 (2024)

Velocity and Kinetic Energy Decomposition of the Deep Western Boundary Current in a Semi-Enclosed Basin

Felipe Vilela-Silva^a, Dante C. Napolitano^a, Daniel Santos^b, Joseph H. LaCasce^c, Jonathan Gula^d, Damien Desbruyères^a, Kurt L. Polzin^e, Xavier Carton^d

^a IFREMER, FR; ^b University of São Paulo, BR; ^c University of Oslo, NORW; ^d UBO, FR; ^e WHOI, USA

The identification of features that change the transport of North Atlantic Deep Water (NADW) is crucial for understanding the variability of the Atlantic Meridional Overturning Circulation (AMOC). The Deep Western Boundary Current (DWBC) transports the NADW across the Atlantic. Recently, Brum et al. (2023) reported a nearly stationary DWBC anticyclone within the Jequitinhonha Basin, centred at 14°S, 36°W, using model output. The shape of the basin allows for the existence of both a stationary anticyclone and higher-frequency oscillations, such as local flow-topography interactions and flow instabilities.

In this work, we decompose the velocity at 14°S to characterize the dominant modes of oscillation and propagation at the deep limb of the AMOC at the centre of the Jequitinhonha Basin. We found that the first mode captures 56% of the total variance of the system and behaves like the anticyclone (Fig. 1, left). As expected, the anticyclone mode only has a major impact on the peaks of energy variability for the periods longer than 80 days. The residual oscillation mode (Fig. 1, middle, right, and other modes) dominates the power spectrum density at higher frequencies when compared to the anticyclone mode,

Does the residual mode peak locally or is it part of the DWBC instabilities and advection into the basin? In this study, we explore the origin and possible consequences of the residual mode for the larger-scale flow.

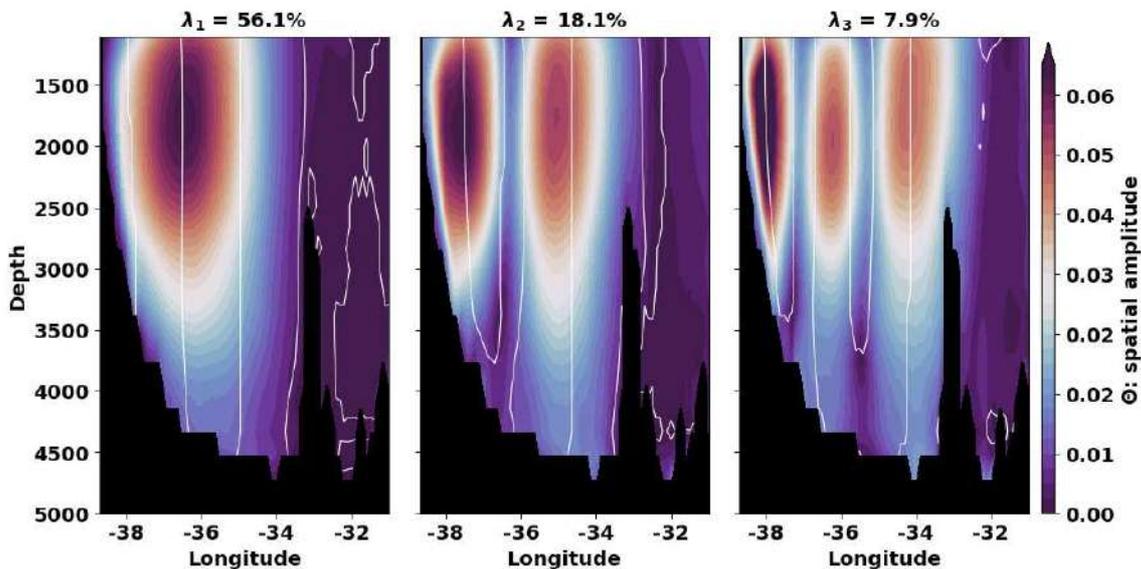


Figure 1: The first three spatial amplitudes after decomposing the complex empirical orthogonal modes of the meridional velocity within the DWBC at 14°S. The white contours show the changes in spatial phase of each mode from -90°, 0, and 90°. We use an ocean model with a 0.1° resolution and 75 vertical layers.

¹ Brum, et al. "Energetics of eddy–mean flow interactions in the deep western boundary current off the northeastern coast of Brazil." *Deep Sea Research Part I: Oceanographic Research Papers*, 193 (2023).

Submesoscale SST fronts reconstruction

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In the ocean, submesoscale structures are known to be highly dynamic areas that capture 50% of vertical movements¹. These motions enable upward nutrient fluxes into the surface layers, which stimulate primary production, a key element of the food web^{2,3}. However, physical and biological processes involved in these structures are very difficult to observe due to their spatial (1-50 km) and temporal (1-10 days) scales. The SWOT (Surface Water and Ocean Topography, NASA-CNES) altimetric mission will allow us to observe the surface dynamic of these fine structures over a wide path under the satellite track by providing SSH (*Sea Surface Height*) measurements at high resolution of 5 to 10 km.

The question which arises is whether a reconstruction of SST (*Sea Surface Temperature*) submesoscale fronts at high resolution from SWOT-like data (geostrophic velocities deduced from SSH) and AMSR-E-like data (SST at low resolution) is possible. For that purpose, new tools based on a previous Lagrangian study⁴ validated in an idealized context have been developed. In this perspective, reconstruct high resolution SST fronts would be particularly important for quantifying the strain field at very fine scales.

The present work deals with a systematic sensitivity study aimed at validating the new SST Lagrangian tools by means of a high-resolution numerical simulation of Primitive Equations (GIGATL1⁵) in the Gulf Stream region. SSH and SST fields are initially filtered so that a wide range of satellite resolution is covered (10 to 100 km). These filtered data allow to quantify the SST reconstruction sensitivity to the scales contained both in the forcing and SST field.

The analysis of SST fields (Figure 1), SST gradients fields and spectra reveal that submesoscale fronts and filaments are reconstructed at very fine scales in position and amplitude particularly when SSH presents a high resolution. As for the time of convergence, it appears to be short of the order of 2-3 days on average.

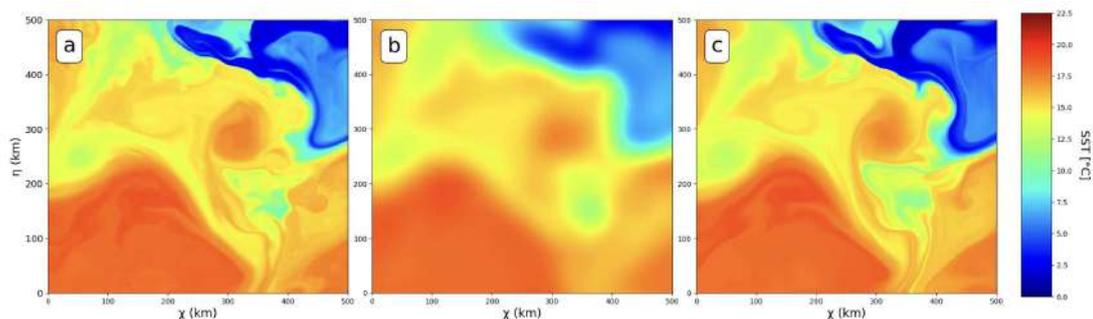


Figure 1: SST field reconstruction in the Gulf Stream area with new Lagrangian tools for SST 100 km - SSH 50 km: a) *True* SST (GIGATL1), b) Low resolution SST, c) Reconstructed SST. **NB**: zoomed area of the initial reconstructed field.

¹Klein & Lapeyre, *Annual Reviews*, **1(1)**, 351–375 (2009)

²Siegelman et al., *Nat. Geosci.* **13**, 50–55 (2020)

³Lévy et al., *Geophysical Research Letters*, **39** (2012)

⁴Berti & Lapeyre, *Ocean Modelling* **76**, 59-71 (2014)

⁵Gula et al., *Zenodo*, <https://doi.org/10.5281/zenodo.4948523> (2021)

Diffusion of internal tides by geostrophic turbulence

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As internal waves propagate, they interact with background flows, topography, and other waves. Weak but sustained interactions such as refraction and advection by a non-uniform background flow lead to scattering: The waves retain their frequency whilst their energy is redistributed across wavenumbers, in a process that can be described statistically. In the WKB limit, this scattering process is well approximated by a diffusion equation that depicts the spreading of wave energy on the constant frequency cone in wavenumber space¹. In this presentation, we use idealized simulations based on a hydrostatic primitive-equation model to investigate the performance of the spectral diffusion approximation for internal tides scattered by geostrophic turbulence. Specifically, we focus on the contribution to the spectral diffusion from the Doppler shift induced by the turbulent background flow. The corresponding diffusion equation predicts both an isotropization and a forward cascade of wave energy¹. Particular emphasis is placed on the latter aspect, with the aim of identifying the time scales associated with this energy cascade in the simulated ocean.

¹Kafiabad et al., *J. Fluid Mech.* **869**, R7 (2019)

Mean flow generation in two-dimensional forced stratified turbulence: uprising of enslaved modes

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Quasi-horizontal layers are ubiquitous in stably stratified flows. In the case of numerical simulations of forced stratified turbulence in periodic domains, the layers can take the form of the so-called “shear modes”, also known as “vertically sheared horizontal flows” (VSHF), i.e. horizontal flow purely uniform along the horizontal and varying only along the vertical¹². These shear modes are observed both in three-dimensional and two-dimensional numerical simulations of stratified turbulence³⁴⁵⁶⁷.

In order to better understand their origin, we perform numerical simulations of two-dimensional strongly stratified flows forced by a steady mode with a single wavenumber of the form $\sin(k_{xf}x)\sin(k_{zf}z)$. It is shown that such deterministic forcing leads to a transition to turbulence and the formation of horizontal layers (figure 1) in the same way as for random stochastic forcing. The characteristics of the flows and layers are studied depending on the Froude and Reynolds numbers. In addition, the present forcing allows us to precisely track the sequence of events leading to a transition to turbulence and the emergence of layers. A triadic instability first develops leading to the exponential growth of pairs of wavevectors that resonate with the forced wavevectors. The quadratic interactions of these resonant modes with the forcing drive also the growth of several non-resonant modes. Since the forcing comprises wavevectors that are symmetric with respect to the horizontal, there exist non-resonant modes with the same horizontal wavenumber and different vertical wavenumbers. Hence, the quadratic interactions between the latter modes excite a second generation of enslaved modes, among which, some have a zero horizontal wavenumber and a non-zero vertical wavenumber, i.e. are VSHF. Such mechanism of formation of a mean flow via non-resonant modes is similar to the resonant quartets of inertial waves in rotating fluids⁸⁹.

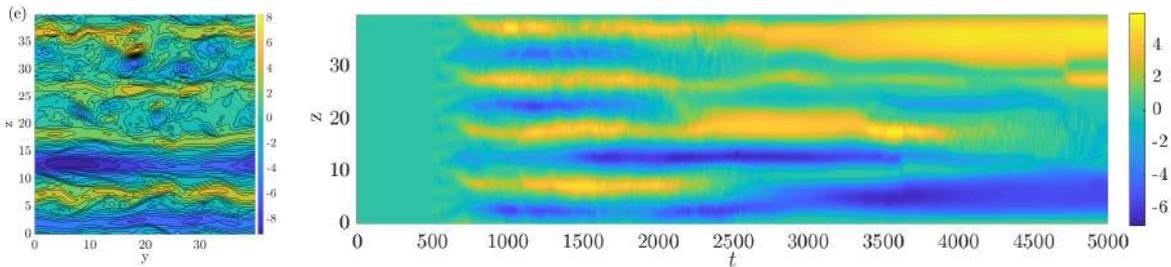


Figure 1: Horizontal velocity field at $t = 2100$ (left) and space-time diagram of the horizontal mean flow (right) in two-dimensional forced stratified turbulence for $Re = 8800$ and $F_h = 0.4$ with $k_{xf} = k_{zf} = 2\pi/10$.

¹Smith, *Contemporary Mathematics* **283**, 91–106 (2001)

²Smith and Waleffe, *J. Fluid Mech.* **451**, 145–168 (2002).

³Laval et al., *Phys. Rev. E* **68**, 03630 (2003)

⁴Lindborg, *J. Fluid Mech.* **550**, 207–242 (2006)

⁵Augier et al., *J. Fluid Mech.* **769**, 403–443 (2015).

⁶Kumar et al., *J. Turbulence* **18**, 219–239 (2017)

⁷Linares, PhD thesis, Université Grenoble Alpes (2020).

⁸Newell, *J. Fluid Mech.* **35**, 255–271 (1969)

⁹Smith and Waleffe, *Phys. Fluids* **11**, 1608–1622 (1999).

Three-dimensional structure of anticyclonic vortices in a stratified rotating fluid

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We experimentally study the three-dimensional structure of anticyclonic vortices in a linearly stratified fluid characterised by a Brunt-Väisälä frequency N and rotating at angular velocity $f/2$. The vortex is generated by the injection of a fluid with the same density as the ambient, as done in previous studies^{1,2,3,4}. The resulting vortex exhibits an initial Rossby number $Ro_0 = \Omega_0/f = -0.5$, where Ω_0 is its initial maximum angular velocity. PIV in horizontal planes at various vertical positions z is used to measure the velocity fields, allowing reconstruction of the three-dimensional structure of the vortex. A parametric study is conducted by varying the injection volume V_i , the flow rate Q_i , the stratification N , and the Coriolis parameter f . The azimuthal velocity v_θ at each instant t can be well modelled by the profile

$$v_\theta(r, z) = \Omega \frac{L^{1+n}}{r^n} \left[1 - \exp\left(-\frac{r^{1+n}}{L^{1+n}}\right) \right] \exp\left(-\frac{z^2}{H^2}\right), \quad (1)$$

where Ω denotes the maximum angular velocity, L the characteristic radius, H the semi-thickness, and the parameter n controls the decay of the velocity in the radial direction (r). This new model, with n in the range $1.5 \leq n \leq 3.5$, fits the experimental data better than the model with a Gaussian angular velocity in the radial direction used previously^{3,4}. For $N/f > 1$, the anticyclone remains axisymmetric and stable (figure 1(a)); however, as $N/f \rightarrow 1$, the anticyclone becomes unstable, exhibiting a tripole structure (figure 1(b)). When stable, the growth of the vortex is approximately characterised by diffusive scaling laws $L/L_0 = \sqrt{1 + C_L t / (L_0^2 / \nu)}$ and $H/H_0 = \sqrt{1 + C_H t / (H_0^2 / \nu)}$, with ν representing the kinematic viscosity. The diffusion coefficients C_L and C_H are found to depend on N/f . In addition, direct numerical simulations (DNS) and simulations under geostrophic and hydrostatic balances⁴ are performed, both of which show good agreement with the experimental observations. Furthermore, DNS reveals that the instability when $N/f \rightarrow 1$ is first due to a gravitational instability (i.e. the total density gradient is locally positive), whose perturbations later cause the vortex to evolve into a tripole.

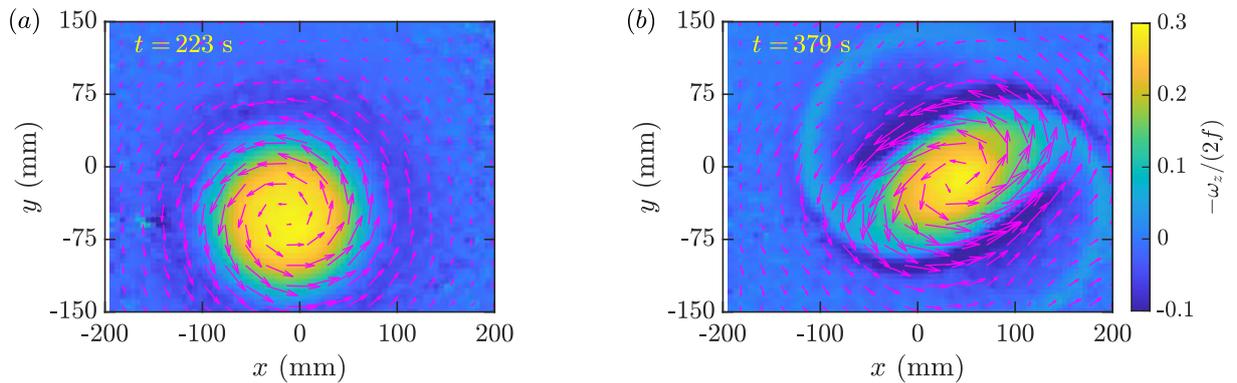


Figure 1: Velocity fields in the mid-horizontal plane, superimposed on the normalised vorticity field $-\omega_z/(2f)$ for: (a) a stable anticyclone at $t = 223$ s with $N = 0.86 \text{ rad s}^{-1}$, $f = 0.42 \text{ rad s}^{-1}$, $V_i = 500 \text{ mL}$, and $Q_i = 2.5 \text{ mL s}^{-1}$; (b) an unstable anticyclone at $t = 379$ s with $N = 0.86 \text{ rad s}^{-1}$, $f = 0.84 \text{ rad s}^{-1}$, $V_i = 500 \text{ mL}$, and $Q_i = 3.6 \text{ mL s}^{-1}$.

¹Griffiths & Linden, *Journal of Fluid Mechanics* **105**, 283-316 (1981).

²Hedstrom & Armi, *Journal of Fluid Mechanics* **191**, 535-556 (1988).

³Aubert et al., *Journal of Fluid Mechanics* **706**, 34-45 (2012).

⁴Facchini & Le Bars, *Journal of Fluid Mechanics* **804**, 688-711 (2016).

Vortex vertical alignment over topography

Jean Reinaud¹, ¹ *University of St Andrews, St Andrews, UK*

The presence of bathymetry affects the evolution of vortices. For example, Lacasce et al. (2024)¹ showed that decaying turbulence leads to the formation of a large, persistent anticyclone over a basin. The authors indicate that this anticyclone is the result of mergers of smaller anticyclones. Other authors have found similar results. Recently, Reinaud et al. (2025)² have investigated the merger of two cyclonic vortices lying in the upper-layer of a two-layer quasi-geostrophic system. The authors showed that indeed cyclones merge faster when lying over a seamount due to a topographic ‘ β -drift’. The authors also confirmed that cyclones tend to be unstable and break into pieces over basins. By symmetry of the QG equations, the reverse is true for anticyclones. This leads to a preferential formation of strong and persistent cyclones over seamounts and anticyclones over basins.

In the present contribution, we consider the other main interaction which makes vortices grow in size: their vertical alignment. We consider two cyclonic vortices lying in different layers. We first consider a three-layer system where the two vortices occupy the upper and middle layers respectively. We recover similar trends: cyclones can align from further apart when lying over a seamount compared to a flat bottom. They tend to break into pieces when lying over a basin. Similar trends are also observed in a two-layer system where the lower vortex shares the same layer as the bathymetry.

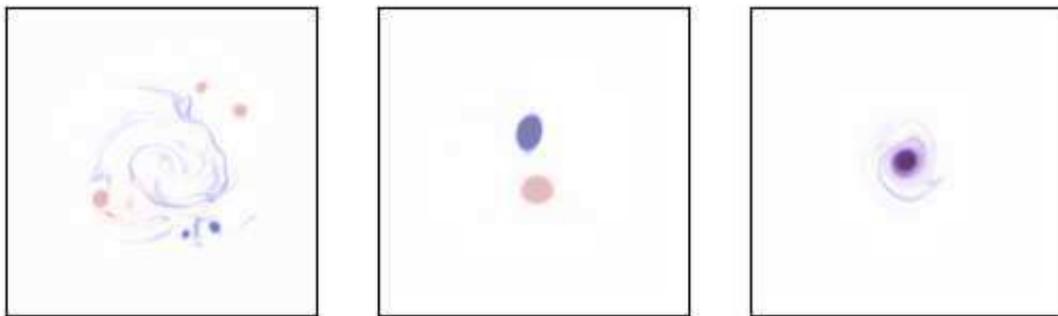


Figure 1: Top view over the upper and middle layers of a three-layer system at $t = 349$ for a basin (left), a flat bottom (middle) and a seamount (right). Vortices are initially distant by 3.5 times their radius. Their radius is 3 times the deformation length in each layer. The Gaussian seamount/basin has a characteristic radius 3 times the one of the vortices.

¹Lacasce et al. *J. Fluid Mech.*, **979**:A32, 2024.

²Reinaud et al. *submitted*, 2024

Defining Mesoscale Eddies Boundaries from in situ Observations and Theory

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In the ocean, mesoscale eddies play an important role in enhancing air-sea interactions and promoting large-scale mixing. They are generally referred to as “coherent” structures because they are organized, rotating fluid elements that propagate within the ocean and have long lifetimes (months or even years). Sometimes, they are described as “materially coherent” since their closed trajectories allow the transport of water masses from one region to another. Due to the limited availability of in situ ocean observations, eddies have primarily been characterized using satellite observations, numerical simulations, or relatively idealized geophysical fluid dynamics methods. In particular, further work is needed to understand their three-dimensional boundaries—regions where eddies lose their coherence.

In this study, using mesoscale eddies (both surface- and subsurface-intensified) sampled during nine oceanographic cruises—eight in the Atlantic Ocean (during the EUREC4A-OA, M124, MSM60, MSM74, M160, HM2016611, KB2017606, and KB2017618 experiments) and one in the Indian Ocean (Physicien 2011 experiment)—we propose a new criterion based on Ertel Potential Vorticity to define eddy boundaries at the mesoscale. These boundaries appear as regions of finite horizontal extent, characterized by a local extremum of the vertical and horizontal components of EPV (Figure 1). They are found to be closely related to the presence of a distinct water mass in the core (relative to the background) and the steepening of isopycnals due to eddy occurrence and dynamics.

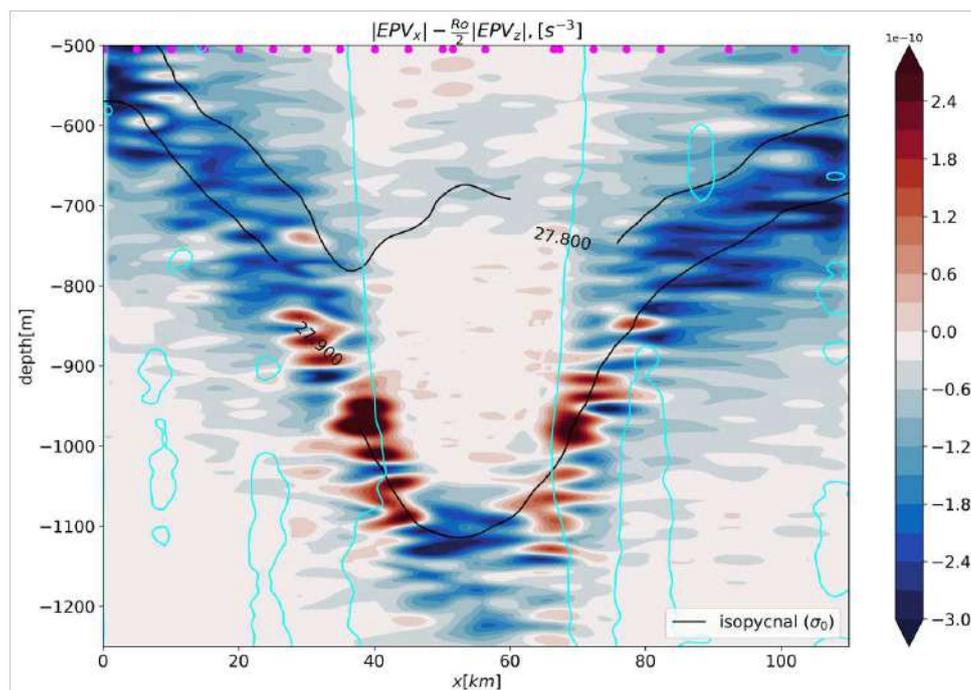


Figure 1: Boundary of an anticyclonic eddy in the Lofoten Basin

Experimental Observation of Oceanic Convection on the Coriolis Platform

Max Coppin^{1,2}, Bruno Deremble¹, Joel Sommeria² and Maria Eletta Negretti²

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The deepening of the oceanic mixed layer under wind forcing plays a crucial role in oceanic and climate dynamics. To better understand the dynamics of this mixed layer, we use a laboratory experiment, which is a large-scale version of the seminal experiments of Kato and Phillips (1969). In a rotating tank, we first create a stratified flow by adding successive layers of water with a warmer temperature. Then, by suddenly changing the rotation rate of the tank, we impose a stress at the interface between the fluid and the tank. A key innovation of our study is the inclusion of rotation its influence on the entrainment process. A particular focus is given to radial dynamics, addressing a major limitation of the original Kato and Phillips (1969) experiments.

Leveraging the unique capabilities of the Coriolis platform (LEGI - Grenoble) and a range of measurement techniques, including stereoscopic PIV, volumetric PIV and LIF we explore the dynamics of the mixed layer at an unprecedented scale, with focus on the **erosion of stratification** induced by frictional stress and the determination of scaling laws governing the resulting turbulent entrainment. Figure 1 shows the dynamics of the mixed layer (grey zone at the bottom) and the stratified flow (black area at the top), with a characteristic Kelvin-Helmholtz instability eroding the upper stratified layer.

An analytical model has been developed as well¹, extending the scaling laws proposed by Pollard et al. (1973) for the deepening of the mixed layer.

This theoretical analysis highlights the role of the Ekman dynamics and inertial oscillations generated by the wind stress impulse to erode the mixed layer. We find that the shear at the base of the mixed layer is mostly driven by the stationary Ekman response and that inertial oscillations play only a secondary role in this process.

This study is part of a broader experimental initiative on the Coriolis platform to develop a comprehensive database of mixed layer dynamics under various forcings (mechanical and thermal forcing) across a wide range of geophysical parameters (rotation, stratification and aspect ratio). These results will be highly valuable for improving parameterizations in ocean models.



Figure 1: Visualization of entrainment in a vertical plane. The bottom plate rotates at a higher rate than the overlying water column. The dark upper layer, which is temperature-stratified, is progressively mixed with the dye contained in the underlying mixed layer.

¹Coppin et al., *In prep* (2025)

Interaction of Near-Inertial Waves with an Anticyclone

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¹ Durham University, ² University of Edinburgh, ³ University of California San Diego

Anticyclonic vortices in the ocean interact with near-inertial waves, leading to modifications in both wave and vortex dynamics. On the wave side, near-inertial wave energy becomes focused and trapped within anticyclones, elevating energy levels in the vortex core (see figure 1). This process is partly explained by the presence of trapped near-inertial eigenmodes, which are readily excited by an initial wave with a horizontal scale much larger than the vortex radius. We investigate this mechanism using a reduced model of near-inertial dynamics and validate its theoretical predictions against high-resolution numerical simulations of the three-dimensional Boussinesq equations. In the linear approximation, the model predicts eigenmode frequencies, spatial structures, and a near-inertial wave energy signature characterized by an approximately time-periodic, azimuthally invariant pattern. On the vortex side, the anticyclone undergoes modifications governed by wave-averaged geostrophic balance, where wave-induced feedback alters potential vorticity through a contribution proportional to the Laplacian of the kinetic energy density of the waves. Using direct numerical simulations of the Boussinesq equations, we quantitatively assess the ability of wave-averaged geostrophic balance theory to describe the modified vortex dynamics.

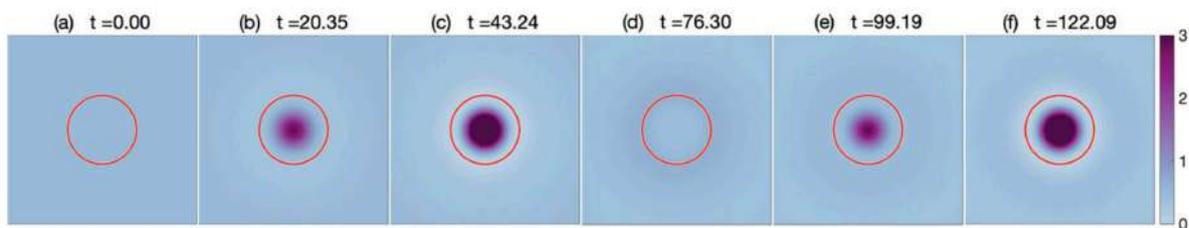


Figure 1: Horizontal slices of wave kinetic energy for a high-resolution Boussinesq simulation initialised by an inertial wave and a Gaussian vortex.

When GFD meets DDG

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Current community models are formidable tools for simulating ocean dynamics over a wide range of scales in configurations that are as realistic as possible. However, being the result of decades of evolution, they are also rather rigid when it comes to exploring radical changes. Yet, these radical changes are becoming increasingly urgent. In this talk I will focus on one central change: the transport.

The transport is fundamentally an inviscid process: it stirs, it does not mix ; it conserves the energy and it materially transports the Potential Vorticity. In the discrete world of numerical modelling, slightly relaxing these rules brings very appealing solutions. The key ingredient is to embed the dissipation into the transport, a solution known as Implicit Large Eddy Simulations. While it may look as an ad-hoc technique, it turns out that the Discrete Differential Geometry (DDG) provides a solid framework for this solution. Figure1 illustrates how the mixing and the dissipation can be handled by the numerics alone, without any explicit sub grid-scale closure. The technique can be summarized briefly as: momentum is not a vector, it is a differential 1-form and, the transport of differential forms should be done with a discretized Lie derivative. We illustrate the benefits of this technique on a few iconic GFD flows.

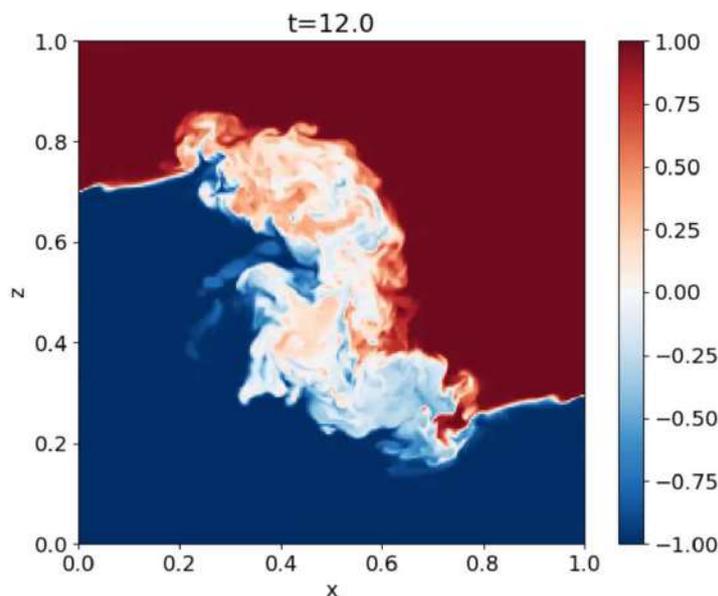


Figure 1: Mixing of buoyancy driven by a Kelvin Helmholtz instability, using an ILES.

Exploring cyclone-anticyclone asymmetry using the balanced ellipsoidal vortex at finite Rossby number

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Large-scale flows in the ocean and atmosphere contain vortices, whose dynamics are strongly influenced by the Earth's rotation, the Coriolis effect, as well as the effects of density stratification. As the sense of the planetary rotation is fixed, it affects cyclonic (anticlockwise) and anticyclonic (clockwise) vortices differently, leading to an asymmetry in their dynamical behaviour. This asymmetry has been observed in large-scale observations of ocean eddies, as well as in numerical simulations. Despite these many studies, there is still much that is not understood about the factors that influence this asymmetry.

Many of the characteristics of geophysical vortices have been elicited through idealised models. Here we consider one such model, an ellipsoid of uniform potential vorticity (PV). This ellipsoidal vortex is solved for the case of a “balanced” model, i.e. a system of equations which take account of the effects of rotation and stratification and where all the dynamics are controlled by the evolution of the potential vorticity field. These equations can be derived from the full equations by expanding the variables in the Rossby number. At first order we recover the quasi-geostrophic (QG) equations, whereas at second order we obtain the so-called QG+1 equations. We solve these equations for the case of the ellipsoidal vortex, obtaining analytical solutions up to second order in the Rossby number. We consider both the case of the isolated vortex and in the presence of a background shear flow that mimics the effect of surrounding vortices. We find equilibria and analyse their linear stability to determine the vortex characteristics at the margin of stability for a given background flow. As the QG solutions depend linearly on the PV, there is no dynamical difference in the behaviour of cyclonic and anticyclonic vortices at this order, only the sign changes. However the solutions up to the second order contain a linear and a quadratic term in the PV which, when combined, cause an asymmetry in dynamical behavior.

The ellipsoidal vortex solutions capture cyclonic-anticyclonic asymmetry in the rotation rate, with isolated anticyclones rotating faster than cyclones. In the presence of a background horizontal strain flow the horizontal cross section of the vortices deform, with cyclonic vortices becoming more deformed than anticyclones. Instead a background vertical shear tends to tilt the vortex from an upright position having a greater effect on anticyclonic vortices with the strongest asymmetry occurring for large values of vertical shear. Overall the results reveal for a vortex in the presence of a background shear flow that the most resilient cyclonic vortices are slightly prolate (greater vertical height than horizontal extent), while anticyclonic vortices tend to be more oblate.

The Impact of Stratification on Surface-Intensified Eastward Jets in Turbulent Gyres

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We investigate the impact of stratification on the formation and persistence of turbulent eastward jets in the ocean (like the Gulf Stream and Kuroshio extensions)¹. Using a wind-driven, two-layer quasi-geostrophic model in a double-gyre configuration, we construct a phase diagram to classify flow regimes.

The parameter space is defined by a criticality parameter ξ , which controls the emergence of baroclinic instability, and the ratio of layer depths δ , which describes the surface intensification of stratification. Eastward jets detaching from the western boundary are observed when $\delta \gtrsim 1$ and $\xi \gtrsim 1$, representing a regime transition from a vortex-dominated western boundary current² to a zonostrophic regime characterized by multiple eastward jets. The emergence of the coherent eastward jet is further addressed with complementary 1.5-layer simulations and explained through both linear stability analysis and turbulence phenomenology. In particular, we show that coherent eastward jets emerge when the western boundary layer is stable, and find that the asymmetry in the baroclinic instability of eastward and westward flows plays a central role in the persistence of eastward jets, while contributing to the disintegration of westward jets.

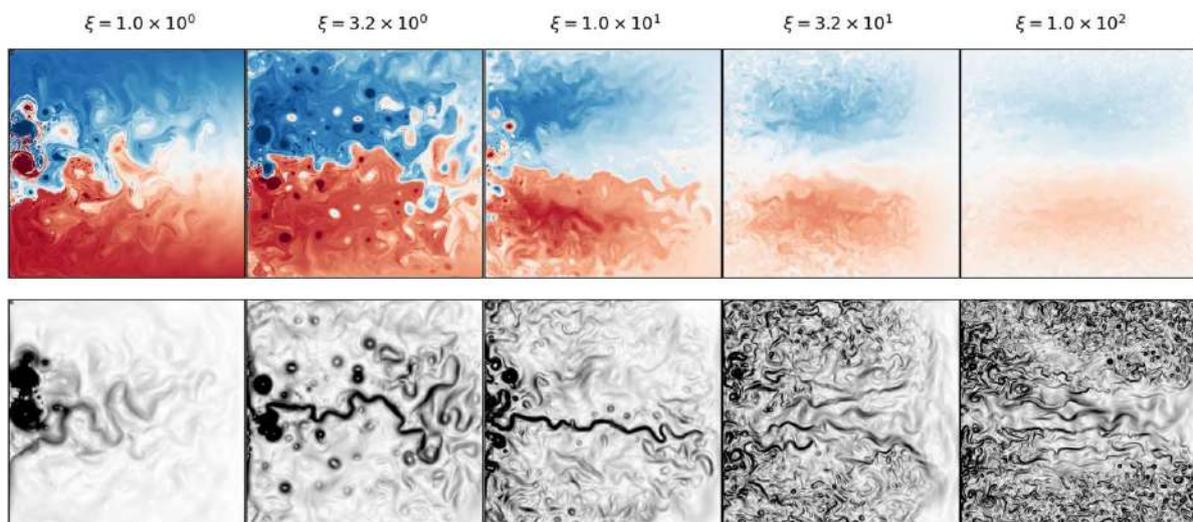


Figure 1: Impact of stratification on the formation of eastward jets detaching from western boundary currents. The upper row shows the potential vorticity, and the lower row the norm of the flow velocity. Stratification decreases from left (low ξ) to right (large ξ). The oceanic eastward jet is situated in the midst of a transition between a vortex gas regime (left, strong stratification) and a zonostrophic regime (right, weak stratification).

¹Miller et al., under review for publication in *Journal of Physical Oceanography* (<https://arxiv.org/abs/2411.05660>).

²Miller et al. *Physical Review Fluids* **9**, (2024)

Turbulent Energy Spectra in a Convectively Driven Baroclinic Flow

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and Peter L. Read¹

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⁴ University of Aberdeen, UK

Geophysical turbulence, such as that near the mid-latitude tropopause, plays a crucial role in atmospheric dynamics by regulating large-scale circulation and energy transfer. To investigate these processes, we employ a rotating annular laboratory model with a free top surface and a conical bottom plate that mimics the beta effect with the fluid depth decreasing toward the centre. The flow is driven by thermal convection localised around the inner and outer walls, enclosing a central annular baroclinic zone¹. Across a rotation rate range of 0.05 to 1.14 rad/s with an applied temperature difference between 11.6 and 12.8 K (corresponding to thermal Rossby numbers $0.028 < Ro_T < 15$), we measured horizontal velocity components at multiple levels via particle image velocimetry, revealing rich flow structure and dynamics. As rotation increases, kinetic energy spectra in the bulk baroclinic region start to exhibit a power-law scaling approaching -3 at large scales, transitioning to a shallower slope in the inertial range. Near the top surface, this -3 scaling is replaced by a shallower slope of ~ -2.2 , with flow characteristics associated with finer scale vorticity structures. Spectral flux analysis reveals a forward energy cascade in the inertial range and an inverse energy transfer at length scales greater than the first baroclinic deformation radius, consistent with the conversion of potential to kinetic energy via baroclinic instability. Across the parameter space, the spectra are predominantly shaped by horizontally non-divergent, rotational flow, with minor contributions from divergent components. This may be related to the low buoyancy frequency-to-Coriolis coefficient ratio ($0.007 < N/2\Omega < 0.16$), in contrast to recent findings with a much shallower system².

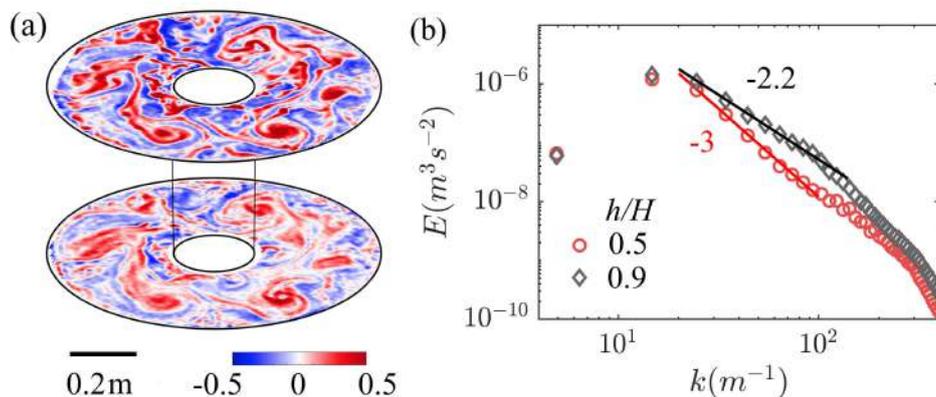


Figure 1: (a) Snapshot of the vertical relative vorticity component at two heights, corresponding to normalized distances of $h/H = 0.5$ and 0.9 to the outer edges of the bottom plate, where $H = 25.8$ cm represents the maximum fluid depth. The vertical separation between the snapshots is not to scale. (b) Kinetic energy spectra at the same two levels.

¹Scolan et al., *Experiments in Fluids* **58(6)**, 75 (2017)

²Rodda et al., *Journal of the Atmospheric Sciences* **77(8)**, 2793-2806 (2020)

Phytoplankton response to oceanic vortex perturbations

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Daniele Iudicone³ and Bruno Buongiorno Nardelli¹

¹ CNR-Institute of Marine Sciences, IT; ² Università degli Studi di Padova, IT; ³ Stazione Zoologica Anton Dohrn, IT; ⁴ Laboratoire d'Océanographie Physique et Spatiale/UBO, FR

The oceanic motion at mesoscale (20-200 km) and sub-mesoscale (0.5-20 km) is highly populated by oceanic vortices (eddies)¹. Eddies sustain marine photosynthesis by modulating the vertical transport of nutrients from the deep layers to the euphotic zone. Contrary to the widely accepted paradigm of simple pumping mechanisms, the dynamics of this vertical exchange is dominated by the perturbations of eddy shape with respect to simplified circular trajectories². Here we demonstrate how eddy distortion impacts phytoplankton dynamics, using a numerical simulation based on the Regional Oceanic Modelling System. The simulation is configured to investigate the 3D dynamics of a cyclonic eddy in an idealized ocean, initialized through analytical functions and accounting for cyclogeostrophic balance³. The evolution of the biogeochemical component is driven by a Nutrient-Phytoplankton-Zooplankton-Detritus model⁴.

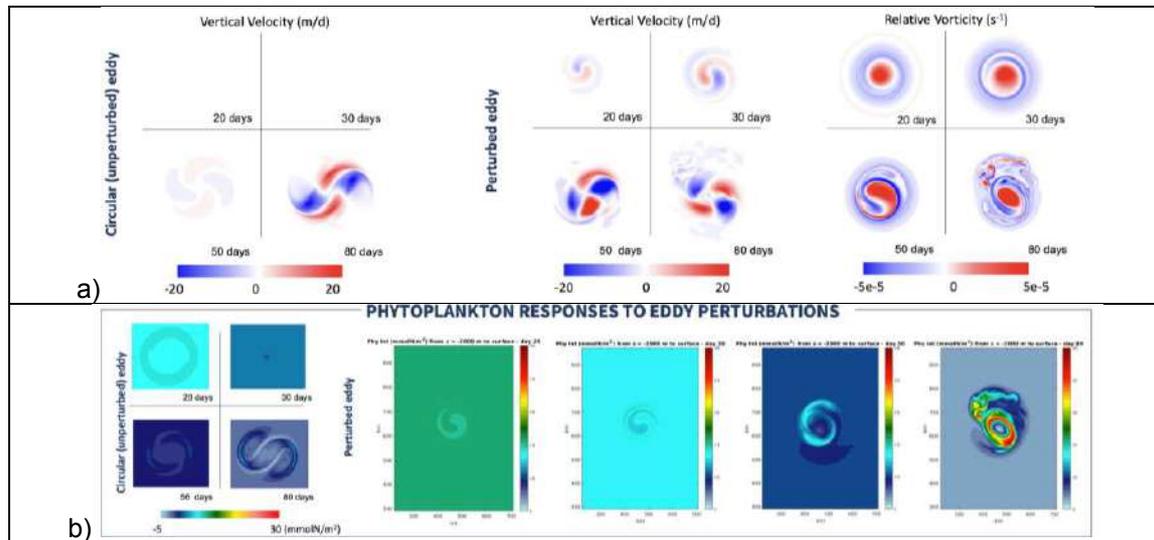


Figure 1 a) vertical velocities and relative vorticity patterns for circular and perturbed eddies; b) vertically integrated Phytoplankton concentrations for circular and perturbed eddies.

Perfectly circular and perturbed cyclones (generated by adding artificial perturbations to the circular case) are inter-compared in terms of physical and bio-geochemical responses. Eddy perturbations induce an enhancement of vertical velocities in the early stages of the eddy life, whose patterns follow vortex Rossby waves propagation, eventually yielding a Phytoplankton accumulation at the eddy periphery. Advanced Lagrangian diagnostics, based on particle releases at the deep-chlorophyll maximum depth, provide further insights into the underlying mechanisms, suggesting that the final phytoplankton distribution is shaped by the interplay of vertical currents and the intensification of horizontal currents associated with small-scale features.

¹ Carton. *Fronts, Waves and Vortices in Geophysical Flows*, 61-108 (2019) (2010)

² Buongiorno Nardelli. *Journal of Geophysical Research: Oceans*, 118(10), 5609-5624 (2013)

³ Ciani et al., *Geophysical & Astrophysical Fluid Dynamics*, 110(1), 23-49 (2016)

⁴ Koné et al., *Glob. Biogeochem. Cycles* 19:GB4021 (2005)

Characterizing Mixing-Length Growth and Melt Rates at the Ice-Ocean Interface

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The recent dramatic and unprecedented changes in the Arctic, characterized by a rapid decrease in sea ice extent¹, are among the major consequences of climate change, which is altering the fully coupled ice–air–ocean system². At the ice–ocean interface, one of the key physical processes is double-diffusive convection, a mechanism describing the convective mixing of fluids driven by the interplay between salinity and temperature gradients. This phenomenon is thought to play a critical role in regulating the salt and heat balance in polar regions but remains poorly parameterized in global climate models³. This underscores the need for detailed small-scale studies using direct numerical simulations in idealized settings.

Using two-dimensional high-resolution numerical simulations, we systematically investigate the influence of the Lewis number and the initial conditions on both the melt rate and mixing-length growth. Starting with homogeneous initial conditions, we provided a detailed characterization of the mixing lengths for both temperature and salinity fields. Our findings revealed two distinct algebraic behaviors: diffusive growth for salinity and linear growth for temperature. Although the scaling exponents appear to be universal, the corresponding coefficients depend on the Lewis number. Additionally, we found that the presence of salty stratification influences the growth of both salinity and temperature. Salt stratification enhances the dynamics of the salt mixing layer while depleting the dynamics of the temperature, resulting in a diffusive regime. For all Lewis numbers, the melt rate undergoes two phases of decays $\propto t^{-0.5}$. The nonlinear stage of the growth dynamics is characterized by a jump, and possible slight deviations in the $\propto t^{-0.5}$ decay rates. Importantly, the stratification does not affect this decay rate, suggesting that there is a decoupling between the dynamics of the mixing length and the melt rate.

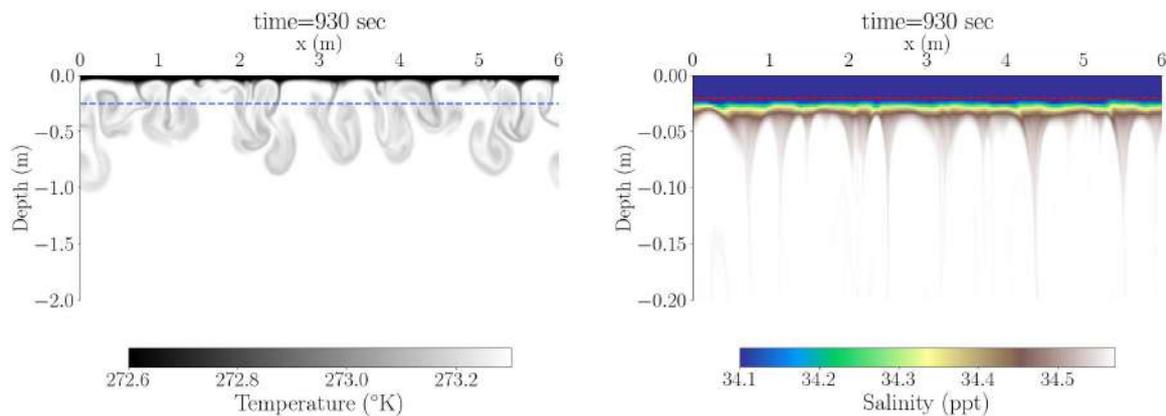


Figure 1: Snapshots of the temperature and salinity fields in the z - x plane, obtained from the 2D simulation with $Le = 10$ and 2048^2 collocation points. Dashed lines correspond to the mixing length.

¹Perovich & Richter-Menge, *Annu. Rev. Mar. Sci.* **1**, 417–441 (2009)

²Lenn et al, *Ocean mixing*, 275-299 (2022)

³Rosevear et al., *J. Phys. Oceanogr.* **52(10)**, 2589-2608 (2022)

Steadily propagating modons in 3D quasi-geostrophic models

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Modons, or dipolar vortices, are common coherent structures in the ocean and atmosphere. Modons persist over long time periods and are known to break down due to background gradients in potential vorticity, commonly resulting from gradients in the Earth's rotation or topographic slopes. However, modons are typically studied in very idealised one- and two-layer quasi-geostrophic (QG) models which do not account for depth-dependent flow features, such as stratification and baroclinicity. Here, I will present a new semi-analytical method for finding modon solutions to three-dimensional quasi-geostrophic models, starting from the layered QG model and moving on to the fully three-dimensional case.

I will also present some results from a recent numerical study of the evolution of a baroclinic modon over long timescales. In the presence of the beta-effect (arising from gradients in planetary rotation), we observe new breakdown mechanics where symmetry breaking leads to wave generation and nonlinear adjustment. These adjusted modons persist as a quasi-steady weakly-radiating vortex over long times. An example of this symmetry breaking is given in Figure 1 which shows the potential vorticity field of a modon during the breakdown phase.

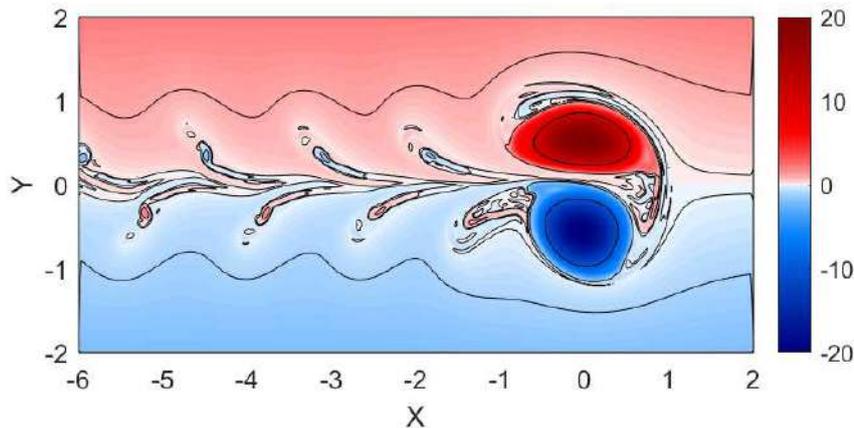


Figure 1: A dipolar vortex breaking down due to a background potential vorticity gradient.

Why Surface Quasi-Geostrophy is a poor model

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The Surface Quasi-Geostrophic (SQG) model has been a popular model for studying the dynamics of the tropopause, surface temperature and also ocean surface flows. The model is a special case of the three-dimensional QG model in which the interior potential vorticity is uniform, but a general surface temperature or buoyancy field is permitted at both the upper and lower boundaries. This field is materially conserved in the absence of diabatic or viscous processes. Potential vorticity inversion (a linear operation in the QG model) allows one to recover the flow field (and all other dynamical and thermodynamical fields) everywhere in the domain. Only the (geostrophic) two-dimensional velocity field at each surface is required to evolve the system in time. This feature has made the model particularly desirable, as the full three-dimensional flow development may be described simply by the evolution of a scalar field at one or both boundaries. However, that flow field is also known to be much less regular than that in conventional two-dimensional flows (or in the interior of three-dimensional QG flows). Small-scales are much more active, leading to roll-up of small-scale filaments and, for some piecewise-constant scalar distributions, a scale cascade leading to a finite-time singularity in tracer contour curvature. This enhanced small-scale activity also leads to a growth of all three vorticity components. In particular, vertical vorticity may grow rapidly, implying that the Rossby number, Ro , may not remain bounded. SQG theory (and QG theory in general) is derived assuming $Ro \ll 1$, and the leading-order fields are all assumed to be $\mathcal{O}(Ro)$. However, if one starts at any finite Ro , say to compare against the full primitive-equation model, then eventually Ro may exceed unity in magnitude, violating the assumptions the theory is predicated upon. Indeed the absolute vertical vorticity may become negative, a situation known to be necessary for inertial instability. Comparisons with the full primitive equations show that SQG fails to predict the subsequent dynamics, which ultimately leads to both inertial and static instability, and overturning isentropic/isopycnal surfaces.