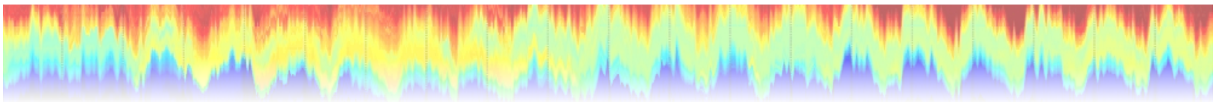

New challenges in internal wave dynamics

Book of abstracts

14-16 Oct 2015
Lyon
France

NewWave: New challenges in internal wave dynamics

Owing to density stratification and rotation, the ocean and the atmosphere support internal waves. Either through direct turbulent mixing following wave breaking, or through other non-linear effects, internal gravity waves play a key role in momentum and energy budgets. Yet the scale separation between wave dynamics and the large scale circulations makes their numerical and theoretical study very challenging. Indeed, current resolutions of general circulation models can not resolve internal waves, whose effect must therefore be parameterized.

On the one hand, physical properties of internal wave dynamics are often addressed in idealized numerical or laboratory experiments that isolate the salient features of the dynamics. On the other hand, parameterizations in realistic settings have to address different issues related to the full complexity of the dynamics and of its numerical implementation. Finally, in situ observations offer both new problems for idealized studies and proxies to be compared with numerical models, with the inherent difficulty that such measurements are sparse in time and space.

Our goal in this interdisciplinary workshop is to familiarize physicists and atmosphere/ocean scientists with ongoing research outside of their field, and possibly fertilize new work between those groups. The half-day sessions will be organized as follows :

- Internal waves : physical properties (2 sessions)
- Internal waves in the ocean (2 sessions)
- Internal waves in the atmosphere (1 session)

This three day workshop will gather around 50 participants. The aim is to have long survey lectures allowing for a thorough discussion and understanding, as well as long breaks and poster sessions for informal scientific discussions.

Invited speakers

U. Achatz, D. Bourgault, P.-P. Cortet, T. Dauxois, A. Delache, S. Joubaud, N. Grisouard, A. Koch-Larrouy, A. Melet, A. Naveira Garabato, A. Ponte, R. Plougonven, G. Vallis, J. Vanneste, K. Winters

Table of contents

Internal waves : physical properties

Analytical solutions describing tidal conversion over ocean ridges

Felix Beckebanze *† [1], Leo Maas‡ [2], Gerard Sleijpen [1]

[1] Mathematical Institute, Utrecht University (UU) – Postbus 80010 3508 TA Utrecht, Netherlands
[2] Royal Netherlands Institute for Sea Research - NWO (NETHERLANDS) – Netherlands

Analytical solutions are constructed of small-amplitude internal waves in an inviscid, uniformly-stratified ocean. Internal waves are generated by barotropic tides over irregular bottom topography. In this process barotropic tidal energy is generally lost to baroclinic internal waves in a process known as tidal conversion. For a discrete family of ocean ridges, having finite support, tidal conversion is absent. It is studied how tidal conversion appears under smooth deformations of this family of ocean ridges. The presented solutions are the first that analytically prescribe internal wave generation over families of ridges, including, for exceptional parameter values, ridges without any tidal conversion.

*Speaker
†Corresponding author: f.beckebanze@uu.nl
‡Corresponding author: maas@nioz.nl

Internal waves in tidal stratified estuaries and fjords

Daniel Bourgault *† [1], Peter Galbraith , Cédric Chavanne

[1] Institut des sciences de la mer de Rimouski (CANADA) (ISMER) – 310, allée des Ursulines Rimouski, QC, G5L 3A1, Canada

Tidal stratified estuaries and fjords are favourable environments for the generation of internal waves. Being fairly narrow and confined, they offer the hope that the full life cycle of naturally-occuring nonlinear internal wavetrains, from generation to propagation and dissipation, could be captured from field experiments. These environments are sometime presented in the literature as being sort of "natural laboratories". The reality is that even in those environments internal waves behave in complex manners that are difficult to observe and apprehend. In this presentation, a variety of field observations of nonlinear internal waves collected in the Saguenay Fjord (Canada) will be presented with the goal to identify and discuss some challenges we are facing in terms of measuring and understanding the behaviour of internal waves in natural environments.

*Speaker
†Corresponding author: daniel_bourgault@uqar.ca

Field observations of internal ship wakes in a fjord

Pascal Bourgault * [1], Daniel Bourgault† [1], Peter Galbraith [1], Cédric Chavanne [1]

[1] Institut des sciences de la MER de Rimouski - ISMER (CANADA) – Canada

This study presents new observations of ship-generated internal waves collected in the stratified waters of the Saguenay Fjord, Canada. The internal wave signature of nine cargo ship passages were captured from a mooring equipped with thermistors and an acoustic Doppler current profiler (ADCP), as well as from shore-based georectified images. Furthermore, en-route ADCP and echo-sounder measurements were collected from a research boat that steamed across the wake of two passing ships, revealing the internal wake structure shortly after being generated. The analysis shows that some ships first generated a single 3 m amplitude internal wave with a phase speed around 1.1 m/s followed by a wavetrain composed of 2 to 5 waves of slightly smaller amplitudes (≈2.5 m) and slower phase speeds (0.41 to 0.75 m/s). Attempts are made to relate the properties of the observed ship-generated internal waves to ships characteristics in the hope of establishing empirical relationships that could help develop and test future theories on ship-generated internal wakes.

*Speaker

†Corresponding author: daniel_bourgault@uqar.ca

Energy Cascade in Internal Wave Attractors

Christophe Brouzet * [1]

[1] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure - Lyon – 46 allée d'Italie 69007 Lyon, France

A question of paramount importance in the dynamics of the oceans is related to the cascade of mechanical energy in the abyss and its contribution to mixing. Here, we propose a unique self-consistent experimental setup that models a cascade of triadic interactions transferring energy from large-scale monochromatic input to multi-scale internal wave motion.
This setup is based on internal wave attractors. Experiments are here carried out in a trapezoidal test tank filled with linearly stratified fluid. Energy is injected into the system via the oscillatory motion of a vertical wall and internal wave velocity fields are measured with a standard PIV technique. Internal wave attractors are prone to parametric subharmonic instability (PSI), which transfers energy from the attractor to a pair of secondary waves.

As the forcing amplitude increases, PSI produces several pairs of secondary waves, creating a cascade of triadic interactions which produces internal-wave motion with a rich multi-peak discrete frequency spectrum embedded into a continuous spectrum of weaker magnitude. We show, for the first time, experimental explicit evidence of a wave turbulence framework for internal waves using energy spectra.
Finally, we show how beyond this regime, we have a clear transition to a cascade of small-scale overturning events which induces significant mixing.

*Speaker

Disentangling inertial waves from eddy turbulence in a forced rotating turbulence experiment

Antoine Campagne * [1], Pierre-Philippe Cortet† [1], Frédéric Moisy‡ [1], Basile Gallet§ [2]

[1] Fluides, automatique, systèmes thermiques (FAST) – Université Paris XI - Paris Sud, CNRS : UMR7608 – bat. 502 91405 ORSAY CEDEX, France
[2] Service de physique de l'état condensé (SPEC - URA 2464) – CEA, CNRS : URA2464 – SPEC - URA 2464, CEA/Saclay, Orme des Merisiers, F-91191 GIF SUR YVETTE CEDEX, France

We present a spatio-temporal analysis of a statistically stationary rotating turbulence experiment, aiming to extract a signature of inertial waves, and to determine the scales and frequencies at which they can be detected. The analysis uses two-point spatial correlations of the temporal Fourier transform of velocity fields obtained from time-resolved stereoscopic particle image velocimetry measurements in the rotating frame. We quantify the degree of anisotropy of turbulence as a function of frequency and spatial scale. We show that this space-time-dependent anisotropy is well described by the dispersion relation of linear inertial waves at large scale, while smaller scales are dominated by the sweeping of the waves by fluid motion at larger scales. This sweeping effect is mostly due to the low-frequency quasi-two-dimensional component of the turbulent flow, a prominent feature of our experiment which is not accounted for by wave turbulence theory. These results question the relevance of this theory for rotating turbulence at the moderate Rossby numbers accessible in laboratory experiments, which are relevant to most geophysical and astrophysical flows.

*Speaker
†Corresponding author: ppcortet@fast.u-psud.fr
‡Corresponding author: moisy@fast.u-psud.fr
§Corresponding author: basile.gallet@cea.fr

Influence of the multipole order of the source on the decay of an inertial wave beam in a rotating fluid

Pierre-Philippe Cortet *† [1], Nathanaël Machicoane [1], Bruno Voisin [2], Frédéric Moisy [1]

[1] Fluides, automatique, systèmes thermiques (FAST) – Université Paris XI - Paris Sud, CNRS : UMR7608 – bat. 502 91405 ORSAY CEDEX, France
[2] Laboratoire des écoulements géophysiques et industriels (LEGI) – Université Joseph Fourier - Grenoble I, Institut polytechnique de Grenoble (Grenoble INP), CNRS : UMR5519 – 1025 Rue de la piscine - BP 53 38041 GRENOBLE CEDEX 9, France

We analyze theoretically and experimentally the far-field viscous decay of a two-dimensional inertial wave beam emitted by a harmonic line source in a rotating fluid. By identifying the relevant conserved quantities along the wave beam, we show how the beam structure and decay exponent are governed by the multipole order of the source. Two wavemakers are considered experimentally, a pulsating and an oscillating cylinder, aiming to produce a monopole and a dipole source, respectively. The relevant conserved quantity which discriminates between these two sources is the instantaneous flow-rate along the wave beam, which is non-zero for the monopole and zero for the dipole. For each source the beam structure and decay exponent, measured using particle image velocimetry, are in good agreement with the predictions.

*Speaker
†Corresponding author: ppcortet@fast.u-psud.fr

Nonlinear internal waves: review of some recent and useful theoretical results -

Thierry Dauxois * [1]

[1] Laboratoire de Physique à l'ENS de Lyon (LPENSL) – CNRS : UMR5672, École Normale Supérieure (ENS) - Lyon – 46 allée d'Italie 69007 Lyon, France

I will review recent results of stratified fluids, illustrating the fascinating properties of internal gravity waves. I will in particular discuss three different physical mechanisms: internal wave reflection, mean flow generation and parametric subharmonic instabilities. I will mostly emphasize theoretical results but also discuss related experimental observations.

G. Bordes, A. Venaille, S. Joubaud, P. Odier, T. Dauxois, Physics of Fluids 24, 086602 (2012) - Experimental observation of a strong mean flow induced by internal gravity waves.

B. Bourget, H. Scolan, T. Dauxois, M. Le Bars, P. Odier, S. Joubaud, Journal of Fluid Mechanics 759, 739 (2014) -
Finite-size effects in parametric subharmonic instability.

H.H. Karimi, T.R. Akylas, Journal of Fluid Mechanics 757, 381 (2014) -
Parametric subharmonic instability of internal waves: locally confined beams versus monochoromatic wavettrains.
T. Kataoka, T.R. Akylas, Journal of Fluid Mechanics 769, 621 (2015) -
On three-dimensional internal gravity wave beams and induced large-scale mean flows.

*Speaker

Investigating internal wave interactions with quasi-geostrophic turbulence

Michael Dunphy * [1], Aurelien Ponte [1], Patrice Klein [1]

[1] Laboratoire de physique des océans (LPO) – Université de Bretagne Occidentale (UBO), INSU, Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), CNRS : UMR6523, Institut de recherche pour le développement [IRD], Institut Universitaire Européen de la Mer (IUEM) – Z.I. Pointe du Diable B.P. 70 29280 Plouzané, France

Two high resolution satellite altimeters are currently under development (SWOT, COMPIRA) with scheduled launches in about five years time. These instruments will provide sea-surface height data at very high spatial resolution and accuracy which will capture mesoscale/submesoscale turbulence and the sea-surface signature of barotropic and baroclinic waves. Techniques for removing the barotropic signals are established, however removing the baroclinic signals is an outstanding problem largely due to phase incoherence with respect to the astronomical forcing. To better understand the source of the phase incoherence, we conduct numerical experiments where we propagate a coherent low-mode internal tide through a turbulent field produced by an unstable jet. We separate the model fields into a slow turbulent part and a fast wave part by an averaging/projection process, and also project onto vertical modes for per-mode analysis. The results show that the coherent wave field loses coherence following the interaction, and further show that a modest amount of energy (1-5%) is scattered to higher vertical wave modes. Lastly we employ an analytic approach to explore the physical mechanisms leading to the incoherence.

*Speaker

Damping of Geostrophic Fronts by Oceanic Internal Waves, Critically Reflecting off the Sea Surface

Nicolas Grisouard *† [1]

[1] Department of Physics (UofT Physics) – Department of Physics, 60 St. George St., Toronto, Ontario, M5S 1A7, Canada, Canada

Within oceanic fronts, due to the sloping isopycnals and associated thermal wind shear, the possible directions of the group velocity of inertia-gravity waves (IGWs) depart from the classical St Andrew's cross. However, waves oscillating at the Coriolis frequency, f, keep one of these directions horizontal, while the other direction allows for vertical propagation of energy. This implies the existence of critical reflections of such inertial waves off the sea surface, after which incident wave energy cannot escape. This is analogous to the classical critical reflection of IGWs in a quiescent medium off a sloping bottom. We present a series of numerical experiments exploring parameter space that highlight properties of critical (frequency = f), forward (frequency > f), and backward (frequency < f) reflections. In particular, we report on irreversible energy exchanges between IGWs and geostrophically-balanced frontal flows that are enabled by friction and the modification of IGW-physics at fronts. We also show analytically that this is exacerbated during critical reflections where intense frictional effects under the surface induce a net transfer of energy from the balanced flow to ageostrophic motions, which are subsequently dissipated. Forward reflections are also favorable to triadic resonant interactions and therefore to turbulence which is weak in our simulations, but likely to be fully developed under oceanic conditions. The existence of this non-linear flow activity further increases the extraction of geostrophic energy from the front. On the other hand, backward reflections inhibit triadic interactions and, consequently, such "spectacular" energy exchanges.

*Speaker

†Corresponding author: nicolas.grisouard@physics.utoronto.ca

Interactions between near-inertial waves and mesoscale motion in the ocean

Vanneste Jacques * [1]

[1] University of Edinburgh (UoE) – King's Buildings, Edinburgh EH9 3DF, United Kingdom

Wind forcing of the ocean generates a spectrum of inertia-gravity waves that is sharply peaked near the local inertial (or Coriolis) frequency. The corresponding near-inertial waves (NIWs) are highly energetic and play a significant role in the slow dynamics of the ocean at large and meso-scales. Using an asymptotic model originally derived by Young & Ben Jelloul (1997), I will discuss some of the properties of NIWs, focussing on their interactions with the mesoscale flow to explain their observed vertical propagation and their concentration in anticyclones. I will then introduce a new coupled model which captures the two-way interaction between NIWs and mesoscale flow. The model is derived using generalised Lagrangian mean theory and preserves energy and an action. Using these conservation laws, I will will show how NIWs act as an energy sink for the mesoscale flow through a process of 'stimulated wave generation'.

*Speaker

Wave field and zonal flow generated by a librating disk

Stéphane Le Dizès * [1]

[1] Institut de Recherche sur les Phénomènes Hors Equilibre (IRPHE) – Ecole Centrale de Marseille, Aix Marseille Université, CNRS : UMR7342 – Technopole de Chateau-Gombert - 49 rue Joliot Curie - BP 146 - 13384 MARSEILLE cedex 13, France

In this work, we provide an exact viscous solution of the linear wave field generated by librating a disk (harmonic oscillation of the rotation rate) in a stably stratified rotating fluid. The zonal flow (meanflow correction) generated by the nonlinear interaction of the wave field is also calculated in the weakly nonlinear framework. We focus on the low dissipative limit relevant for geophysical applications and for which the wave field and the zonal flow exhibit generic features. General expressions are obtained which depend on the disk radius a, the libration frequency f, the rotation rate Om of the frame, the buoyancy frequency N of the fluid, its kinematic diffusion nu and its thermal diffusivity kappa. When the libration frequency w is in the inertia-gravity frequency interval (min(Om,N)< w < max(Om,N)), the presence of conical internal shear layers is observed in which the spatial structures of the harmonic response and of the meanflow correction are provided. At the point of focus of these internal shear layers on the rotation axis, the largest amplitudes are obtained: the angular velocity of the harmonic response and the meanflow correction are found to be O(eps E^(-1/3)) and O(eps^2 E^(-2/3)) respectively where eps is the libration amplitude and E= nu/(Om a^2) is the Ekman number. We show that the solution in the internal shear layers and in the focus region is at leading order the same as that generated by a Dirac oscillating ring source of axial flow placed at the edge of the disk.

*Speaker

Experiments on topographies lacking tidal conversion

Leo Maas * [1], Alexandre Paci [2], Bing Yuan [3]

[1] Royal Netherlands Institute for Sea Research (NIOZ) – Netherlands
[2] Meteo France – Météo France – France
[3] Utrecht University (IMAU) – Netherlands

In a stratified sea, internal tides are supposedly generated when the tide passes over irregular topography. It has been shown that for any given frequency in the internal wave band there are an infinite number of exceptions to this rule of thumb. This 'stealth-like' property of the topography is due to a subtle annihilation of the internal waves generated during the surface tide's passage over the irregular bottom. We here demonstrate this in a lab-experiment. However, for any such topography, subsequently changing the surface tide's frequency does lead to tidal conversion. The upshot of this is that a tidal wave passing over an irregular bottom is for a substantial part trapped to this irregularity, and only partly converted into freely propagating internal tides.

*Speaker

Experimental study of the role of rotation on Parametric Subharmonic Instability (PSI)

Paco Maurer * [1], Sylvain Joubaud† [2], Philippe Odier‡ [2]

[1] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure (ENS) - Lyon – 46 allée d'Italie 69007 Lyon, France
[2] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure - Lyon – 46 allée d'Italie 69007 Lyon, France

The ocean is a stratified fluid whose dynamics is believed to be driven by internal waves as they affect mixing and energy transport. In oceanic conditions, rotation plays also a role on the propagation of internal waves and on their instabilities, particularly when it comes to non-linear interaction between internal waves such as Parametric Subharmonic Instability. This instability consists in a destabilized primary wave emitting spontaneously two secondary waves of different wavelength and pulsation and provides an efficient way to transfer energy from large to small scale.

We investigate experimentally the effect of rotation on the PSI threshold of a beam of monochromatic gravito-inertial waves. We observed that in addition to modifying the threshold, rotation also affects the secondary waves character- istics. Experimental results are compared to theoretical predictions and show, on a certain range of rotation, a lowered PSI threshold associated with a richer spectrum of secondary waves pulsation. For certain rotation frequencies, un- expected evanescent waves emerge from PSI.

*Speaker
†Corresponding author: sylvain.joubaud@ens-lyon.fr
‡Corresponding author: philippe.odier@ens-lyon.fr

Internal waves patterns in the wake of a 3D body towed in a two-layer fluid.

Matthieu Mercier * [1], Laurent Lacaze [1], Olivier Thual [1], Alexandre Paci [2]

[1] Institut de mécanique des fluides de Toulouse (IMFT) – CNRS : UMR5502, Université Paul Sabatier [UPS] - Toulouse III, Institut National Polytechnique de Toulouse - INPT, Université Paul Sabatier (UPS) - Toulouse III – France

[2] Meteo France – Météo France – France

Stratified flows over obstacles are important features in meteorology and oceanography. The characterization of these flows is crucial in order to propose models of geophysical processes such as mixing and ocean circulation or orographic drag in the atmosphere.
For some specific stratification profiles, the energy of internal waves generated by the obstacle can be trapped at a given depth, at the base of the oceanic mixing layer or at the top of the atmospheric boundary layer for instance. This scenario can be modelled by a two-layer stratified fluid for which gravity waves spread at the interface between the two layers.

The work presented here focuses on a two-layer flow over a 3D obstacle, or equivalently, an obstacle towed in a fluid at rest. Experiments performed both in the large-scale flume of CNRM-GAME Toulouse (METEO-FRANCE & CNRS) and in a smaller tank apparatus (IMFT), are presented with a specific attention on the measurement of the 3D wave patterns generated by several 3D objects.
A non-hydrostatic linear analysis is used to describe the observed wave patterns. The experiments highlight the strong influence of the Froude number on the generated waves. More specifically, we investigate the nature of the wake angle obtained from the wave pattern, and discuss a transition from Kelvin to Mach angle.

*Speaker

Iinternal waves interacting with particles in suspension

Diane Micard * [1], Ernesto Horne *

[2], Sylvain Joubaud† [2], Philippe Odier‡ [2]

[1] Laboratoire de Mecanique des Fluides et d'Acoustique (LMFA) – CNRS : UMR5509, Université Claude Bernard - Lyon I (UCBL), Ecole Centrale de Lyon, Institut National des Sciences Appliquées [INSA] - Lyon – 36 Av Guy de Collongue 69134 ECULLY CEDEX, France
[2] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure (ENS) - Lyon – 46 allée d'Italie 69007 Lyon, France

Internal waves are produced as a consequence of the dynamic balance between buoyancy and gravity forces when a particle of fluid is vertically displaced in a stably stratified environment. Geophysical systems such as ocean and atmosphere are naturally stratified and therefore suitable for internal waves to propagate. Furthermore, these two environments stock a vast amount of particles in suspension, which present a large spectrum of physical properties (size, density, shape), and can be organic, mineral or pollutant agents. Therefore, it is reasonable to expect that internal waves will have an active effect over the dynamics of these particles.

In order to study the interaction of internal waves and suspended particles, an idealized experimental setup has been implemented. A linear stratification is produced in a 80×40×17 cmˆ3 tank, in which two-dimensional plane waves are created thanks to the innovative wave generator GOAL. In addition, a particle injector has been developed to produce a vertical column of particles within the fluid, displaying the same two-dimensional symmetry as the waves. The particle injector allows to control the volumic fraction of particles and the size of the column.

The presence of internal waves passing through the column of particles allowed to observe two main effects: the column oscillates around an equilibrium position (which is observed in both the contours and the interior of the column), and the column is displaced as a whole. The oscillations produced on the column are found also beyond the limits of the incoming wave beam. The column is displaced depending on the characteristics of the column, the density gradient, and the intensity and frequency of the wave.

When displaced, the particles within the column are sucked towards the source of waves. The direction of the displacement of the column is explained by computing the effect of the Lagrangian drift generated by the wave over the time the particles stay in the wave beam before settling.

*Speaker
†Corresponding author: sylvain.joubaud@ens-lyon.fr
‡Corresponding author: philippe.odier@ens-lyon.fr

Wave turbulence of internal waves

Nicolas Mordant * [1,2,3]

[1] Laboratoire des écoulements géophysiques et industriels (LEGI) – Université Joseph Fourier - Grenoble I, Institut polytechnique de Grenoble (Grenoble INP), CNRS : UMR5519 – 1025 Rue de la piscine - BP 53 38041 GRENOBLE CEDEX 9, France
[2] Institut Universitaire de France (IUF) – Ministère de l'Enseignement Supérieur et de la Recherche Scientifique – Maison des Universités, 103 Boulevard Saint-Michel, 75005 Paris, France
[3] Université de Grenoble Alpes (UGA) – Universite de Grenoble Alpes – France

Weak turbulence is a theory developed since the 60's as a statistical theory of wave turbulence, i.e. a turbulent state made of a large number of non linear waves. In the limit of weak non linearity, the scale separation between the fast wave oscillation and the slow non linear coupling among wave enables the development of an natural asymptotic theory. This theory is extremely elegant but its validity in real systems is still a matter of debate depending on the physical systems. I will briefly recall our experimental results on vibrated elastic plates and surface waves on water to show that this theory seems to fit (at least qualitatively) the observations. I will then discuss the relevance of this framework to internal waves and present the experiment that we plan to do in Grenoble in the framewaork of my ERC Grant on stratified (wave?) turbulence.

*Speaker

Equilibrium statistical mechanics and energy partition for the shallow water model

Antoine Renaud * [1], Antoine Venaille† [1], Freddy Bouchet‡ [2]

[1] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure - Lyon – 46 allée d'Italie 69007 Lyon, France

[2] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure (ENS) - Lyon – 46 allée d'Italie 69007 Lyon, France

Geophysical flows are highly turbulent, and yet present large-scale coherent structures. Statistical mechanics is a powerful approach allowing to describe this self-organization phenomenon with only a few thermodynamical parameters such as the energy and the enstrophy of the flow. It has been applied with success to several geophysical problems, such as the description of jovian and oceanic vortices. However, due to important technical difficulties, those previous applications were, up to now, limited to the use of quasi-geostrophic models, which do not contain inertia-gravity waves. Here, [1], we generalize the statistical mechanics theory to the shallow water model, which is the simplest model allowing for the presence of inertia-gravity waves. This model captures a direct energy cascade through wave motions and shocks, along with a concomitant inverse energy cascade of the vortical part of the flow. Within the statistical mechanics framework, we predict the emergence of a balanced large scale flow that contains only a fraction of the total energy. The excess energy is stored among small scale fluctuations that can be interpreted as inertia-gravity waves. The theory thus predicts the fraction of energy dissipated through interactions between the vortical part and the wave part of the dynamics.

preprint: Equilibrium statistical mechanics and energy partition for the shallow water model, A. Renaud, A. Venaille, F. Bouchet, arXiv:1505.01356

*Speaker

†Corresponding author: antoine.venaille@ens-lyon.fr

‡Corresponding author: freddy.bouchet@ens-lyon.fr

Geometric focusing of internal waves: experiments versus theory

Natalia Shmakova *† [1], Evgeny Ermanyuk [2,3], Bruno Voisin [1], Jan-Bert Flor [1]

[1] Laboratoire des écoulements géophysiques et industriels (LEGI) – Université Joseph Fourier - Grenoble I, Institut polytechnique de Grenoble (Grenoble INP), CNRS : UMR5519 – 1025 Rue de la piscine - BP 53 38041 GRENOBLE CEDEX 9, France
[2] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure (ENS) - Lyon – 46 allée d'Italie 69007 Lyon, France
[3] Lavrentyev Institute of Hydrodynamics (LIH) – 630090, Novosibirsk, Russia pr. ac. Lavrentyeva, 15 LIH SB RAS Phone: +7(383-2) 33-16-12 Fax: +7(383-2) 33-16-12 E-mail: igil@hydro.nsc.ru, Russia

The interaction of tidal motion with ocean bottom topography results in the radiation of internal gravity waves into the ocean interior, known as the baroclinic tide. Dissipation due to nonlinear breaking is believed to play an important role in the mixing of the abyssal ocean, and therefore in the large-scale ocean circulation.

Over the past five decades the dynamics of particularly diverging internal waves have been considered, such as generated by an oscillating object, see for example Mowbray and Rarity (1967) for a cylinder, or King at al. (2009) and Ermanyuk et al (2011) for a sphere. Wave focusing is known to occur for wave reflection on inclined boundaries (Maas et al. 1997), but the geometric focusing as occurs for oscillating bodies of ring shaped topography is not well known, and only the case studied by B́uhler and Muller (2007) who considered a ring with Gaussian generatrix placed at the bottom is known.

Here we present results on internal waves in a linearly stratified fluid generated by a torus with a circular generatrix of radius a oscillating horizontally with amplitude A. The LIF and PIV techniques are used to measure respectively the isopycnal displacement and the velocity field.

It is shown that for weak oscillation amplitudes (i.e. with Ke = A/a < 0.5) the entire wave field (i.e. structure and amplitude) is in good agreement with the linear theory. With increasing oscillation amplitude wave slopes in the focal zone grow linearly. Overturning occurs for Ke > 0.7. In this case the focal zone radiates waves in the horizontal plane.

Complimentary experiments have been conducted in the Coriolis platform with a large torus of 15 cm generatrix radius and 180 cm diameter (small Froude number, large Reynolds number) to study bimodal and nonlinear effects, and the turbulence in the focal zone.

B́uhler, O. & Muller, C.J., 2007, J. Fluid Mech., 588, 1–28.
Ermanyuk E.V., Flor, J.-B. & Voisin, B., 2011, J. Fluid Mech., 671, 364–383.
King, B., Zhang H.P. & Swinney, H.L., 2009, Phys. Fluids, 21, 116601.
Maas, L.R.M., Benielli, D., Sommeria, J. & Lam, F.P.A., 1997, Nature, 388, 557–561.
Mowbray, D. E. & Rarity, B. S. H., 1967, J.Fluid Mech., 28, 1–16.

*Speaker
†Corresponding author: natalia.shmakova@legi.cnrs.fr

Cyclone-anticyclone asymmetry in gravity wave radiation from vortical flows in rotating shallow water

Norihiko Sugimoto * [1]

[1] Department of Physics, Keio University, Japan – School of Building 2, Room 212, Hiyoshi campus, Keio University, Hiyoshi 4-1-1, Kouhoku-ku, Yokohama, 223-8521, Japan, Japan

Gravity wave radiation from unsteady motions of nearly balanced vortical flows is investigated in rotating shallow water system. The far field of gravity waves from a co-rotating vortex pair is derived analytically by analogy with the theory of aeroacoustic sound wave radiation (Lighthill theory). The Earth's rotation affects not only the propagation of gravity waves but also their source and there is an asymmetry in gravity wave radiation between cyclone pairs and anticyclone pairs. Anticyclone pairs radiate gravity waves more intensely than cyclone pairs and have a local maximum of their intensity at an intermediate f (Coriolis parameter). A numerical simulation is performed with a newly developed spectral method in an unbounded domain. This method is free from wave reflection at the boundary because of a conformal mapping and a pseudo-hyperviscosity that acts as a sponge layer. The numerical results are in excellent agreement with the analytical results. Furthermore, cyclone-anticyclone asymmetry in gravity wave radiation is also found for the case of merging of vortices. N. Sugimoto, K. Ishioka, and K, Ishii, "Parameter sweep experiments on spontaneous gravity wave radiation from unsteady rotational flow in an f-plane shallow water system," J. Atmos. Sci., 65, 273–249 (2008).

N. Sugimoto and K, Ishii, "Spontaneous Gravity Wave Radiation in a Shallow Water System on a Rotating Sphere," J. Meteor. Soc. Japan, 90, 101–125 (2012).

N. Sugimoto, K. Ishioka, H. Kobayashi, and Y. Shimomura, "Cyclone-anticyclone asymmetry in gravity wave radiation from a co-rotating vortex pair in rotating shallow water," J. Fluid Mech., 772, 80–106 (2015).

*Speaker

Geometric focusing of internal waves: linear theory

Bruno Voisin *† [1], Evgeny Ermanyuk [2,3], Natalia Shmakova [1], Jan-Bert Flór [1]

[1] Laboratoire des Écoulements Géophysiques et Industriels – CNRS : UMR5519, Université Grenoble Alpes – BP 53, 38041 Grenoble, France
[2] Lavrentyev Institute of Hydrodynamics – Prospekt Lavrentyev 15, Novosibirsk 630090, Russia
[3] Laboratoire de Physique – CNRS : UMR5672, École Normale Supérieure (ENS) - Lyon – 46 allée d'Italie 69007 Lyon, France

Alongside two-dimensional mechanisms such as the intersection of separate beams (e.g. Smith & Crockett 2014) or between an incident beam and its reflection at a slope (e.g. Grisouard et al. 2013), a specific three-dimensional mechanism is susceptible of amplifying internal gravity waves: the geometric focusing of waves emitted by horizontally curved forcing. Appleby & Crighton (1987) and Simakov (1993, 1994), for simple oscillating objects, then B́uhler & Muller (2007) and Grisouard & B́uhler (2011), for internal tides over circular ocean topography, demonstrated its occurrence theoretically. The first laboratory experiments were conducted at LEGI by Flór (1997, unpublished results), generating internal waves and turbulence with a horizontal circular torus in a stratified fluid; the same approach was repeated by Duran-Matute et al. (2013) for inertial waves in a rotating fluid, experimentally and numerically. Focusing has been identified by Buijsman et al. (2014) in the Luzon Strait in the South China Sea, in the form of enhanced interference between the internal tides over two curved parallel ridges. We present a linear theory of internal wave focusing from annular forcing, for a slender annulus of negligible local curvature. The analysis is applied first to a torus, either complete or partial. Focusing is seen to arise in all cases and yield significant isopycnal slopes, close to overturning, even at low oscillation amplitude. The slopes get higher as the Stokes number increases, changing the beam structure from unimodal to bimodal. Gaussian ocean topography is considered next, either circular or horseshoe-shaped. Focusing is seen to arise as well, though its efficiency is lower owing to the weak topographic slope and oscillation amplitude.

Appleby, J. C. & Crighton, D. G. (1987) J. Fluid Mech. 183, 439–450.
B́uhler, O. & Muller, C. J. (2007) J. Fluid Mech. 588, 1–28.
Buijsman, M. C., Klymak, J. M., Legg, S., Alford, M. H., Farmer, D., MacKinnon, J. A., Nash, J. D., Park, J.-H., Pickering, A. & Simmons, H. (2014) J. Phys. Oceanogr. 44, 850–869.
Duran-Matute, M., Flór, J.-B., Godeferd, F. S. & Jause-Labert, C. (2013) Phys. Rev. E 87, 041001(R).
Grisouard, N. & B́uhler, O. (2012) J. Fluid Mech. 708, 250–278.
Grisouard, N., Leclair, M., Gostiaux, L. & Staquet, C. (2013) Proc. IUTAM 8, 119–128.
Simakov, S. T. (1993) J. Fluid Mech. 248, 55–65; (1994) Wave Motion 19, 11–27.
Smith, S. & Crockett, J. (2014) Exp. Therm. Fluid Sci. 54, 93–101.

*Speaker
†Corresponding author: bruno.voisin@legi.cnrs.fr

Resonant generation and energetics of wind-forced near-inertial motions in a geostrophic flow.

Daniel Whitt * [1]

[1] Department of Applied Mathematics and Theoretical Physics / Centre for Mathematical Sciences (DAMTP/CMS) – DAMTP, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, United Kingdom

A slab mixed layer model and two-dimensional numerical simulations are used to study the generation and energetics of near-inertial oscillations in a unidirectional, laterally sheared geostrophic current forced by oscillatory winds. The vertical vorticity of the current modifies the effective Coriolis frequency, which is equivalent to the local resonant forcing frequency. In addition, the resonant oscillatory velocity response is elliptical, not circular, because the oscillation periodically exchanges energy with the geostrophic flow via shear production. With damping, this energy exchange becomes permanent, but its magnitude and sign depend strongly on the angle of the oscillatory wind vector relative to the geostrophic flow. However, for a current forced by an isotropic distribution of wind directions, the response averaged over all wind angles results in a net extraction of energy from the geostrophic flow that scales as the wind work on the inertial motions times the square of the Rossby number of the geostrophic flow for small Rossby number. For O(1) Rossby number, this sink of geostrophic kinetic energy preferentially damps flows with anticyclonic vorticity and thus could contribute toward shaping the positively skewed vorticity distribution observed in the upper ocean.

Daniel B. Whitt and Leif N. Thomas, 2015: Resonant Generation and Energetics of Wind-Forced Near-Inertial Motions in a Geostrophic Flow. *J. Phys. Oceanogr.*, 45, 181–208.

*Speaker

Linear interfacial and surface waves over periodic bottoms: exact solutions

Jie Yu *† [1], Leo Maas [2]

[1] Stony Brook University (SUNY) – Stony Brook, NY 11794, United States
[2] Royal Netherlands Institute for Sea Research - NWO (NETHERLANDS) – Netherlands

We consider a two-layer fluid, having a general periodic bottom that is confined to the lower layer. In order to determine the free interfacial and surface wave modes of given frequency the lower layer is conformally mapped onto a uniform-depth layer. The map preserves the periodicity of medium (set by the bottom), hence determines the water depth in the transformed plane. The free wave modes are solved by use of Floquet theory, arriving at an infinite matrix determining the frequency-wavenumber relationship. The modes approach the classical interfacial and surface wave solutions in the case of a flat bottom, and an equivalent form of the latter for the interfacial wave mode in the case of a rigid lid. As for the classical, flat-bottom case, over a periodic bottom, the surface wave mode's vertical displacement of the interface is weaker than that of the surface, but is in-phase. By contrast, in the interfacial wave mode, the interfacial wave displacement is the largest and the surface wave displacement is in anti-phase. However, over the periodic bottom, on top of its response at the scale corresponding to the adopted frequency, the interface displacement shows a rapid modulation at bottom scale. This is true both for the interfacial, but most prominently for the surface wave mode.

*Speaker
†Corresponding author: jie.yu.1@stonybrook.edu

Internal tide modeling from laboratory to ocean scales : Hydraulic & Topographic controls

Lucie Bordois * [1,2], Francis Auclair [1], Alexandre Paci [3], Yvan Dossmann [4], Cyril Nguyen [1]

[1] Laboratoire d'aérologie (LA) – CNRS : UMR5560, Observatoire Midi-Pyrénées, INSU, Université Paul Sabatier (UPS) - Toulouse III – 14 avenue Edouard Belin 31400 Toulouse, France
[2] Groupe d'étude de l'atmosphère météorologique (CNRM-GAME) – CNRS : UMR3589, INSU, Météo France – METEO FRANCE CNRM 42 Av Gaspard Coriolis 31057 TOULOUSE CEDEX 1, France
[3] Meteo France – Météo France – France
[4] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure (ENS) - Lyon – 46 allée d'Italie 69007 Lyon, France

Internal tides are involved in the Meridional Overturning Circulation energy balance. The issue about the relative importance of the mechanical and thermodynamical energy sources induces a need for a quantitative evaluation of the energy transfers and for a clear understanding of the physical processes involved in these energy transfers.
In supercritical regions (internal tide generation area with supercritical topographies and hydraulic control) such as the strait of Gibraltar, large topographic variations and strong currents lead to more complex generation mechanisms of internal waves and environmental interactions. This area can be subject to local spectacular breaking and driving turbulence orders of magnitude higher than open-ocean levels. A numerical approach is adopted to explore internal tide regimes in these regions. Simulations are performed using a non-hydrostatic non-Boussinesq free-surface ocean model.
Taking an idealized modeling approach at laboratory scale, a regime analysis has been proposed using and identifying key non-dimensional parameters for internal wave dynamics. This analysis has permitted to characterize a topographic control on vertical modes above supercritical topographies and on high mode solitary wave formation. Then our analysis is applied to two well-known realistic cases: the Strait of Gibraltar and Georges Bank through large eddy simulations. These two oceanographic "supercritical" regions are particularly interesting for their specific topographies and stratification conditions.

*Speaker

Thorpe's scale, Ozmidov's scale and isotopy restored at small scales in freely decaying stratified turbulence.

Alexandre Delache * [1], Louis Gostiaux [2], Fabien Godeferd [2], Claude Cambon [2]

[1] Laboratoire de Mecanique des Fluides et d'Acoustique site de Saint Etienne (LMFA site de Saint Etienne) – CNRS : UMR5509, Université Jean Monnet - Saint-Etienne – École Centrale de Lyon 36, avenue Guy de Collongue 69134 Écully cedex France, France

[2] Laboratoire de Mecanique des Fluides et d'Acoustique (LMFA) – CNRS : UMR5509, Université Claude Bernard - Lyon I (UCBL), Ecole Centrale de Lyon, Institut National des Sciences Appliquées [INSA] - Lyon – 36 Av Guy de Collongue 69134 ECULLY CEDEX, France

Stably stratified homogeneous turbulence (SST) is known to exhibit quasi-horizontal structures organized in vertically sheared layers. These structures are a mix between internal wave and turbulence. Different lengthscales are used to characterise the overturning of buoyancy. The most commonly used in oceanography are Thorpe's scale L_T which is a measure of large-scale vertical overturns and Ozmidov's scale L_o=(epsilon / N^3)^{1/2} (where N is the Brunt-V'ais'al'a frequency and epsilon is the dissipation). Structures larger than L_o are strongly influenced by stratification whereas structures smaller than L_o recover three-dimensional isotropy. L_o and L_T are related by Dillon's relation L_o _~ 0.8 L_T which is observed in the ocean and was also recently checked in Direct Numerical Simulations (DNS). Moreover, the lengthscales L_o and L_T are widely used to analyse data from numerical simulations or from experiments. This shows that a refined description is important for an accurate characterization of turbulent mixing in stratified flows that include large-scale anisotropy and overturnings.

We propose here a parametric study of the scale-by-scale anisotropy using dedicated spectra, as an extension of the lengthscales characterization of SST. In order to analyze further small-scale isotropisation, we present results from high resolution DNS (2048^3 grid points) of freely decaying turbulence at four different stratification rates. They confirm that the Ozmidov scale is a separating scale between anisotropic and isotropic ranges: for moderate stratification, the large scales are preferentially horizontally oriented but the smaller scales recover a classical isotropic behaviour. When stratification is increased, smaller and smaller scales also gradually adopt a quasi horizontal motion. We analyze this anisotropy scale by scale by considering the angle-dependent energy spectrum of velocity and density. Moreover, we separate poloidal and toroidal contributions of velocity to the kinetic energy spectrum, which are respectively linked to waves and vortex motion (similar to the geostrophic/ageostrophic decomposition).

*Speaker

Internal Tides in the Oceans of Icy Moons

Sander Van Oers *† [1], Leo Maas [1], Onno Bokhove [2], Bert Vermeersen [3]

[1] Royal Netherlands Institute for Sea Research -NIOZ (NETHERLANDS) – Netherlands
[2] School of Mathematics - University of Leeds – Woodhouse Lane - University of Leeds - Leeds LS2 9JT United Kingdom, United Kingdom
[3] Delft University of Technology [[DELFT] – Delft University of Technology Postbus 5 2600 AA Delft, Netherlands

One of the most peculiar features on Saturn moon Enceladus is the so-called tiger stripe pattern near its south pole, as first observed in detail by the Cassini spacecraft early 2005. It is generally assumed that the four almost parallel surface lines that constitute this pattern are faults in the icy surface overlying a confined salty water reservoir. Indeed, later Cassini observations have shown that salty water jets are spawned from the faults.

The remarkable spatial regularity of Enceladus' southern polar region fault lines is reminiscent to that observed at the surface of confined stratified fluids by the action of induced internal waves. Both numerical simulations and water tank experiments indicate that wave attractors emerge in gravitationally (radial salt concentration or temperature differences) or rotationally stratified confined fluids as a function of forcing periodicity and fluid basin geometry.

The equations governing internal gravity waves in a stratified ideal fluid possess a Hamiltonian structure. A discontinuous Galerkin finite element method has been developed in which this Hamiltonian structure is discretized, resulting in conservation of phase space and of a discrete analog of energy. This required (1) the discretization of the Hamiltonian structure using alternating flux functions and symplectic time integration, (2) the discretization of a divergence-free velocity field using Dirac's theory of constraints and (3) the handling of the large-scale computational demands due to the three-dimensional nature of internal gravity waves and possibly its narrow zones of attraction.
Laboratory experiments on quasi two-dimensional wave attractors were performed. The forces exerted by wave attractors at the surface a gravitationally stratified fluid were measured. These measurements showed an intensification of wave motion near the reflection point of the attractor. The largest forces were measured near the reflection point of the wave attractor.

*Speaker
†Corresponding author: Sander.van.Oers@nioz.nl

Internal waves : in the ocean

On the fate of topographically-trapped internal tides

Rémi Chassagne * [1], Frédéric Cyr† [2], Leo Maas‡ [3], Andrea Cimatoribus [4], Hans Van Haren§ [4], Daniel Bourgault [5]

[1] Ecole Nationale Supérieure de Techniques Avancées ParisTech (ENSTA ParisTech) – ENSTA ParisTech – 828 Boulevard des Maréchaux, 91120 Palaiseau, France, France

[2] Royal Netherlands Institute for Sea Research -NIOZ (NETHERLANDS) – Netherlands

[3] Royal Netherlands Institute for Sea Research - NWO (NETHERLANDS) – Netherlands

[4] Royal Netherlands Institute for Sea Research (NIOZ) – Netherlands

[5] Institut des sciences de la MER de Rimouski - ISMER (CANADA) (ISMER) – 310, allée des Ursulines Rimouski, QC, G5L 3A1, Canada

The Rockall bank (N-E Atlantic ocean) is known for hosting topographically-trapped diurnal tides that propagates anti-cyclonally around the bank. A recent mooring deployment in this area highlighted a diurnal succession of large amplitude (0 (10ˆ2m)) internal bores propagating upslope onto the bank. Breaking of freely propagating internal tides (such as f < omega < N) are well known to generate such motions. But because the main barotropic tide there is diurnal, our study focuses on one specific case of internal tide where omega < f < N. The results of an analytical mpodel and of a 2D non-hydrostatic model are presented. Results show that the trapped barotropic wave (or Edge wave) alone is sufficient to generate such internal waves. It is also shown that the internal waves generated by these motions cannot escape from the topography, raising questions about where the energy goes.

*Speaker

†Corresponding author: frederic.cyr@nioz.nl

‡Corresponding author: maas@nioz.nl

§Corresponding author: Hans.van.Haren@nioz.nl

Internal waves on the upstream side of a large sill of the Mascarene Ridge: a comprehensive view of their generation mechanisms and evolution

Jose Dasilva * [1,2], Maarten Buijsman [3], Jorge Magalhaes [1]

[1] University of Porto (Porto, Portugal) (U.PORTO) – Departamento de Geociências, Ambiente e Ordenamento do Território – FCUP Rua do Campo Alegre, 687 - 4169-007, Porto, Portugal., Portugal

[2] Interdisciplinary Centre of Marine and Environmental Research (CIIMAR) – Rua dos Bragas 289, 4050-123 Porto, Portugal., Portugal

[3] University of Southern Mississippi (USM) – University of Southern Mississippi, Department of Marine Science, 1020 Balch Blvd, Stennis Space Center, MS 39529, USA, United States

In this paper we aim to clarify the generation of Internal Solitary Waves (ISWs) at work to the east of the Mascarene Plateau (Indian Ocean) using Synthetic Aperture Radar (SAR) imagery and MITgcm fully nonlinear and nonhydrostatic simulations. Realistic representations of stratification and bathymetry are used with asymmetric tidal forcing (including the steady South Equatorial Current which is assumed barotropic in the model) along a 2D transect aligned with the propagation direction of the wave signatures identified in the SAR. The combined flow (i.e. steady and tidal currents) is subcritical with respect to first-mode Internal Waves (IWs), but supercritical with respect to higher wave modes. Different types of nonlinear wave trains with distinct origins (i.e. tidal phase and location) have been identified with the combined aid of model and SAR: 1) large-scale primary mode-1 ISWs evolve from the disintegration of a multimodal baroclinic structure that appears on the upstream side of the sill; 2) mode-2 ISW-like waves that evolve from this same baroclinic structure and are arrested over the sill before being released upstream at the change of flow condition; 3) a large mode-2 lee wave is generated downstream of the sill (i.e. on the west side), which is trapped there during maximum westward tidal flow and released upstream when the tide relaxes; and 4) mode-2 ISW-like waves whose length-scales are O(20 km) appear some 50 km upstream of the sill, after an Internal Tide (IT) beam scatters into the pycnocline, itself originating from critical topography on the leeward (i.e. westward) side of the sill. The underwater sill being investigated is in the mixed-tidal-lee wave regime, where the internal tide release mechanism, lee wave generation and IT beams can coexist. The large-scale mode-2 ISW-like waves that form far upstream from the sill are long-lived features and can be identified in the SAR due to associated short-scale mode-1 ISWs which propagate with the same phase speed, i.e. in resonance. This coupling is also seen in the model, and here it is argued that the formation of those mode-2 ISW-like waves appears to originate from the IT beam after it reflects from the sea surface and interacts with the pycnocline, a generation mechanism referred in the literature as "local generation of ISWs". This IW generation process may be easily overlooked and could be at work in many more regions of the world than previously thought. Deep-Sea Research I 99 (2015) 87–104.

*Speaker

The surface reflection of the internal wave field emitted by a localized submerged stratified turbulent source

Peter Diamessis * [1], Qi Zhou†

[1] Cornell University – United States

The surface manifestation of the internal waves (IWs) radiated by stratified wake of a towed sphere is examined using implicit Large Eddy Simulation. Six simulations are performed at values of sphere-based Reynolds number, Re=5×10ˆ3 and 10ˆ5, and Froude number, Fr=4, 16 and 64, have been performed. An idealized linear stratification extends through the entire computational domain which is chosen to be sufficiently deep and wide to enable the full surface reflection of the radiated waves. The wave-emitting wake is located at a fixed distance of nine sphere diameters below the surface. Extending to a non-dimensional time of $Nt \approx 300$, where N is the buoyancy frequency, the IW field's horizontal wavelength and wave period, are computed at the sea surface through wavelet transforms of the corresponding horizontal divergence signals. The mean observable horizontal wavelength decays with a -1 power law in time indicating that wave dispersion is the dominant process in the far field, as predicted by a Re/Fr-independent linear propagation model. This finding suggests that the most energetic waves observed at the free surface originate from the early-time wake and its adjustment to buoyancy ; questions remain as to how efficient later-time strongly stratified turbulence may be in radiating energetic IWs. The local enrichment ratio of model surfactants scales linear with IW steepness and exceeds an empirically proposed remote visibility threshold. Finally, Lagrangian drifts of the ocean tracer particles produce a local divergence in lateral mass transport, immediately above the wake centerline, an effect that intensifies strongly with increasing Fr.

*Speaker

†Corresponding author: qz76@cornell.edu

Topographically induced mixing : remote versus local

Yvan Dossmann * [1], Ross Griffiths , Andy Hogg , Graham Hughes

[1] Laboratoire de Physique de l'ENS Lyon (Phys-ENS) – CNRS : UMR5672, École Normale Supérieure (ENS) - Lyon – 46 allée d'Italie 69007 Lyon, France

The interaction of balanced abyssal ocean flow with submarine topography is expected to generate both lee waves that can carry energy into the ocean interior and local turbulent mixing near the boundary. The relative amounts of remote and local energy dissipation governs the distribution of mixing within the water column, carrying implications for the evolution of the abyssal stratification and overturning circulation. We report results from laboratory experiments with a topographic ridge towed through a stratified fluid. The experiments span three parameter regimes including linear lee waves, nonlinear flow and an evanescent regime in which wave radiation is weak. Full field density measurements provide the depth-dependence of energy loss to turbulent mixing, allowing separation of the local mixing in the turbulent wake and remote mixing by wave radiation. Remote mixing is significant only for a narrow band of forcing parameters where the flow speed is resonant with internal waves; in all other parameter regimes local mixing close to the topography is dominant. The results suggest that mixing by local nonlinear mechanisms close to abyssal ocean topography may be much greater than the remote mixing by lee waves.

*Speaker

Internal tides in the Indonesian Seas

Ariane Koch-Larrouy *† [1], Dwiyoga Nugroho [1], Agus Atmadipoera [2], Pieter Van Beek [1], Florent Lyard [1], Gurvan Madec [3], Matthieu Legaigne [3], Benoit Tranchant [4]

[1] LEGOS – UMR5566 – 18 ave edouard belin 31401 toulouse cedex 09, France
[2] IPB BOGOR – Indonesie, Bogor, Indonesia
[3] Laboratoire d'Océanographie et du Climat : Expérimentations et Approches Numériques (LOCEAN) – Université Pierre et Marie Curie (UPMC) - Paris VI, CNRS : UMR7159, INSU, Institut de recherche pour le développement [IRD], Muséum National d'Histoire Naturelle (MNHN) – case 100 4 place jussieu 75252 PARIS CEDEX 05, France
[4] CLS – CLS – France

A wide range of values is obtained for dissipation within [10-8, 10-4] W/kg with spots of higher dissipation in the ocean interior correlated with a strong internal tide signal. Deduced Kz values are found between 510-4 to 5 10-1 m2/s, much more higher than open ocean values. Surface mixing, below the base of the mixed layer is found to be very strong above all straits, with values within [10-4, 10-3 m2/s]. Introduced in a model using an adapted parameterisation to the Indonesian archipelago, models show good agreement with the observations, where strong water mass transformation has been previously diagnosed. This additional mixing produce a _˜0.5°C surface cooling and reduces by 20% the overlying deep convection. The El Nino Southern Oscillation (ENSO) amplitude is slightly reduced while the Indian Ocean Dipole/Zonal Mode (IODZM) variability increases. The MJO is also improved in the model. Changes in the coupled system in response tidal mixing are as large as those found when closing the Indonesian Throughflow, emphasizing the key role of IA on the Indo-Pacific climate. This suggests that climate models need to take into account this intensified mixing to properly represent the mean state of the atmosphere and its climate variability. Modeling of the explicit tides show that a small fraction of the internal wave are radiated and dissipate away of the generation site, that was not taken into account in the previous parameterization. Also bottom friction induced by barotropic tides on the shelve may produce significant surface mixing, that may also affect the climate.

*Speaker
†Corresponding author: ariane.koch-larrouy@ird.fr

Worldwide estimates of internal-tide-driven mixing at small-scale abyssal hills

Adrien Lefauve *† [1], Caroline Muller [2], Angélique Melet [3]

[1] DAMTP – Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, United Kingdom
[2] CNRS – Laboratoire d'Hydrodynamique de l'Ecole Polytechnique, Palaiseau, France – France
[3] CNES – Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse, France – France

The breaking of internal tides is believed to provide a large part of the power needed to mix the abyssal ocean and sustain the meridional overturning circulation. Both the fraction of internal tide energy that is dissipated locally and the resulting vertical mixing distribution are crucial for the ocean state, but remain poorly quantified. Here [1] we present a first worldwide estimate of mixing due to internal tides generated at small-scale abyssal hills. Our estimate is based on linear wave theory, a non-linear parameterization for wave breaking and uses quasi-global abyssal hill bathymetry, stratification and tidal data.
We show that a large fraction of abyssal-hill generated internal tide energy is locally dissipated over mid-ocean ridges in the Southern Hemisphere. Significant dissipation occurs above ridge crests, and, upon rescaling by the local stratification, follows a monotonic exponential decay with height off the bottom, with a non-uniform decay scale. We however show that a substantial part of the dissipation occurs over the smoother flanks of mid-ocean ridges, and exhibits a mid-depth maximum due to the interplay of wave amplitude with stratification.

Current tidal parameterizations only account for waves generated at large-scale satellite-resolved bathymetry. Our results suggest that the presence of small-scale, mostly unresolved abyssal hills could significantly enhance the spatial inhomogeneity of tidal mixing, particularly above mid-ocean ridges in the Southern Hemisphere. We link the three-dimensional map of dissipation to abyssal hills characteristics, ocean stratification and tidal forcing, and discuss its potential implementation in time-evolving parameterizations for global climate models.
Lefauve, A., Muller, C. & Melet, A. A three-dimensional map of tidal dissipation over abyssal hills, J. Geophys. Res. (Accepted), 2015.

*Speaker
†Corresponding author: lefauve@damtp.cam.ac.uk

Large current systems affecting Internal Solitary Waves near the Amazon shelf as observed in SAR imagery

Jorge Magalhaes *† [1], Jose Dasilva [2], Maarten Buijsman [3], Paulo Calil [4], Carlos Garcia [4], João Lorenzzetti [5]

[1] University of Porto (Porto, Portugal) (U.PORTO) – Departamento de Geociências, Ambiente e Ordenamento do Território – FCUP Rua do Campo Alegre, 687 - 4169-007, Porto, Portugal., Portugal
[2] University of Porto – Portugal
[3] University of Southern Mississippi – United States
[4] Federal University of Rio Grande – Brazil
[5] National Institute for Space Research (INPE) – Brazil

We present a first account of Internal Solitary Waves (ISWs) on and off the Brazilian Amazon shelf. SAR imagery reveals coherence crest lengths in excess of 200 km, which are first detected near the southern edge of the North Equatorial Counter Current (NECC) and intensify as they run along its main stream. A strong seasonal variability on the ISWs spatial structure and propagation directions is also discuss in light of the NECC, along with its influence in the usual disintegration process of the ITs. On-shelf regions just off the Amazon River mouth are prone to intense and continuous (i.e. not of tidal origin) ISW signatures in the SAR, which are believed to be associated with intricate bottom-topography and flow criticality.

*Speaker
†Corresponding author: jmagalhaes@fc.ul.pt

Internal-wave driven diapycnal mixing in the ocean: parameterizations and climatic impacts

Angelique Melet * [1]

[1] Laboratoire d'études en Géophysique et océanographie spatiales (LEGOS) – CNRS : UMR5566, Institut de recherche pour le développement [IRD], CNES, Observatoire Midi-Pyrénées, INSU, Université Paul Sabatier (UPS) - Toulouse III – 14 avenue Edouard Belin 31400 Toulouse, France

Important sources of energy for internal waves are winds, leading to the generation of near inertial waves, and the flow of sub- and near-inertial currents and barotropic tides over topography in the stratified ocean, leading to, respectively, the generation of internal lee waves and internal tides. The breaking of internal waves represents the main source of diapycnal mixing in the ocean interior. Diapycnal mixing is in turn a crucial driver of the thermohaline circulation and plays a key role in maintaining ocean stratification and in the transport and storage of heat and carbon dioxide.
However, the breaking of internal waves occurs on scales too small to be resolved explicitly in ocean climate models. Physically based parameterizations of the small-scale mixing induced by internal waves are therefore needed for realistic simulation of the ocean and for estimating how mixing might change in a changing ocean.
In this talk, I will present parameterizations of internal-wave driven mixing for ocean models that have been developed as part of the US Climate Process Team on Internal-Wave Driven Mixing (http://www-pord.ucsd.edu/_˜jen/cpt/) and implemented in the NOAA/GFDL's climate model ESM2G. Climate simulations of 1000 years are used to assess the sensitivity of the ocean state to these parameterizations. I will especially focus on the sensitivity of the thermohaline circulation, ocean ventilation, temperature field and of steric sea level to parameterizations of local and remote internal-tide dissipation and of lee-wave driven mixing.

*Speaker

The role of internal waves in the circulation of the Southern Ocean

Alberto Naveira Garabato * [1]

[1] The National Oceanography Centre Southampton (NOCS) – School of Ocean and Earth Science (564 / 17) National Oceanography Centre, Southampton University of Southampton Empress Dock Southampton SO14 3ZH U.K., United Kingdom

The meridional overturning circulation and stratication of the global ocean are shaped critically by processes in the Southern Ocean. This influence is exerted via a set of special dynamics that couple the eastward flow of the Antarctic Circumpolar Current (ACC) with the meridional overturning circulation across the Southern Ocean. Efforts to unravel the dynamics of this coupling have to date emphasised the large-scale circulation's control by wind and buoyancy forcings and by mesoscale eddies generated by baroclinic and barotropic instabilities of the ACC. In this talk, I will review recent evidence from a major UK – US observational programme (the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean, DIMES) pointing to a significant role of internal waves in the zonal and meridional circulations of the Southern Ocean. I will show that the impingement of mesoscale flows onto rough seafloor topography generates internal waves that contribute significantly to dissipating the regional eddy field, arresting ACC jets, and mixing and upwelling water masses across density surfaces.

*Speaker

An Argo-data based validation of the internal gravity wave model IDEMIX

Friederike Pollmann * [1], Carsten Eden , Dirk Olbers

[1] Insitut für Meereskunde, Universität Hamburg (IfM) – Institute of Oceanography Bundesstr. 53 20146 Hamburg, Germany

Breaking internal gravity waves are considered to be a major source of small-scale turbulence, that acts to mix density in the vertical and thus contributes to driving the global overturning circulation. To represent this turbulent mixing consinstently, recently developed parameterizations therefore take internal wave energetics into account. The model IDEMIX ("Internal Wave Dissipation, Energy and Mixing") predicts the propagation and dissipation of oceanic internal gravity waves as well as the corresponding diapycnal diffusivities based on a simplification of the spectral radiation balance of the wave field and can be used as a mixing module for global numerical simulations. The aim of this study is to validate the model through a comparison with observations. Since direct observations of turbulent mixing are sparse, we follow the approach by Whalen et al. (2012) and compute finescale strain variance from Argo-float CTD-profiles to estimate the turbulent kinetic energy dissipation and the related diapycnal diffusivity.
Both the spatial variation as well as the magnitude of the observed energy dissipation rate are in general well reproduced by the IDEMIX-model. Sensitivity experiments show that the dissipation rate's strength and pattern (especially in the Gulf Stream) cannot be explained when mesoscale eddies and the dissipation of their energy are not accounted for. The observed seasonal cycle, too, can in the model only be explained by the seasonal variations in eddy kinetic energy. A detailed fine-tuning of the IDEMIX-module will be attempted based on parameters like the bandwidth of the Garret-Munk spectrum or the symmetrization time scale of the internal wave field, using a global ocean general circulation model with a special focus on seasonal variations. For this validation, the newer version of IDEMIX is used, that not only describes the internal wave continuum but features additional compartments for near-inertial waves and internal tides.

Whalen, C. B., L. D. Talley, and J. A. MacKinnon. "Spatial and temporal variability of global ocean mixing inferred from Argo profiles." *Geophysical Research Letters* 39.18 (2012).
Olbers, Dirk, and Carsten Eden. "A global model for the diapycnal diffusivity induced by internal gravity waves." *Journal of Physical Oceanography* 43.8 (2013): 1759-1779.

*Speaker

Observing and identifying internal waves from space

Aurelien Ponte * [1], Michael Dunphy [1], Patrice Klein [1], Sylvie Le Gentil

[1] Laboratoire de physique des océans (LPO) – Université de Bretagne Occidentale (UBO), INSU, Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), CNRS : UMR6523, Institut de recherche pour le développement [IRD], Institut Universitaire Européen de la Mer (IUEM) – Z.I. Pointe du Diable B.P. 70 29280 Plouzané, France

High resolution images of the ocean surface roughness, temperature, and soon elevation (SWOT altimetric mission launched in 2020) provide an unprecedented view of the near-surface ocean dynamics. One critical difficulty for the correct interpretation of these images lies in the often poor temporal resolution of such data and in our ability to distinguish processes (e.g. balanced mesoscale eddies, submesoscale features, internal waves) which may share comparable spatial scales and interact. This talk will report on recent efforts to develop methodologies that achieve the distinction between the sea level signatures of low-mode internal waves and mesoscale eddies. These methodologies rely on a combination between observations of sea level and sea surface temperature and on the fundamental difference of dynamics between these two processes. High resolution numerical simulations of the propagation of an idealized internal tide through a turbulent eddy field provide testbeds for these methodologies.

*Speaker

Reflection of Internal Waves on a slope

Keshav Raja * [1], Joel Sommeria [1], Chantal Staquet [1], Matthieu Leclair [2], Nicolas Grisouard [3], Louis Gostiaux [4]

[1] Laboratoire des écoulements géophysiques et industriels (LEGI) – Université Joseph Fourier - Grenoble I, Institut polytechnique de Grenoble (Grenoble INP), CNRS : UMR5519 – 1025 Rue de la piscine - BP 53 38041 GRENOBLE CEDEX 9, France

[2] Massachusetts Institute of technology [Cambridge] (MIT) – Massachusetts Avenue Cambridge, MA 02142, United States

[3] Department of Physics (UofT Physics) – Department of Physics, 60 St. George St., Toronto, Ontario, M5S 1A7, Canada, Canada

[4] LMFA – Nikon Imaging Centre@Institut Curie-Cnrs – France

The interaction of internal waves with bottom topography is one of the processes that cause mixing and transport in the ocean. The present study considers the relatively simpler problem of internal waves reflecting from a slope using both laboratory experiments and 3-D numerical simulations. A plane wave, produced using a wave generator, is made to reflect normally on a sloping bottom in a uniformly stratified fluid. We consider both rotating and non-rotating cases. The interaction of the incident and reflected waves produce, apart from higher harmonics, an irreversible wave induced mean flow which grows in time and is localised in the interacting region. The finite extent of the wave generator allows the mean flow to recirculate in the horizontal plane, resulting in a dipolar potential vorticity field. The generation of mean flow and higher harmonics, along with dissipative effects, diminishes the amplitude of reflected wave. We study the momentum and energy budget of the process in order to understand the mechanism of generation of mean flow and its interaction with the wave. The laboratory experiments were carried out on the Coriolis Platform, and the numerical simulations were done using a non-hydrostatic model.

*Speaker

Impact of a mean current on internal tide energy dissipation at the critical latitude

Oceane Richet * [1], Caroline Muller† [1], Jean-Marc Chomaz‡ [1]

[1] laboratoire d'hydrodynamique de l'ecole polytechnique (ladhyx) – Polytechnique - X – France

In many regions of the ocean, the abyssal flow is dominated by tidal flow. A large fraction of the tidal energy input in the ocean is dissipated via the generation of internal waves above rough topography. Idealised simulations suggest that internal tide energy is transferred and dissipated at smallerscales by the formation of a resonant triad between near-inertial waves, internal tides and subharmonics waves. Furthermore, the energy dissipation is enhanced at the critical latitude (28.8°), corresponding to the Parametric Subharmonic Instability (PSI).
In the ocean, the presence of background flow, for instance due to the passage of a mesoscale eddy, can modify energy transfer mechanisms and the amount of energy dissipation. In this study, we investigate the generation and dissipation of internal tides in the presence of a background flow. We use a high-resolution two-dimensional nonhydrostatic numerical model (the MITgcm), with realistic multiscale topography representing the Brazil basin region. The purpose of this study is to understand the impact of the mean flow on the generation and dissipation of tidal waves. Our particular interest is how the maximum of energy dissipation at the critical latitude is impacted by the mean flow.

*Speaker
†Corresponding author: carolinemuller123@gmail.com
‡Corresponding author: jmchomaz@gmail.com

Tidally driven mixing and dissipation in the stratified boundary layer above steep submarine topography

Kraig Winters *† 1

1 Scripps Institution of Oceanography (SIO) – United States

Motivated by the observation that most of the energy converted from barotropic tides to baroclinic internal waves radiates away from steep ridge systems (Ray and Mitchum [1997], Klymak et al, [2006]), we examine the near-boundary flow induced by a low-mode internal tide impinging on a sloping boundary via three-dimensional numerical simulation. Here we consider the 'deep-ocean' case relevant to continental slopes where the topography is supercritical, i.e. steeper than the inclination angle of energy propagation for internal tides. We focus on this regime specifically to exclude the special dynamics associated with critical reflection or the breaking of internal lee waves near the crest of isolated topographic features. The simulations resolve spatial scales within the inertial subrange; the grid spacing is about 1/25th the Ozmidov scale based on the maximum dissipation rate.

Spatial and temporal features of the near boundary flow are presented and the structure observed in the simulations is compared with high-resolution mooring data from above the slope in the Bay of Biscay (van Haren [2006]).The diapycnal diffusivity of the near-boundary flow is estimated by means of a synthetic dye release experiment along with the dissipation rate of kinetic energy. When scaled to ocean conditions, the values obtained are in reasonable agreement with the direct microstructure measurements of Kunze at al [2012]. The overall mixing efficiency is estimated to be 0.15, in good agreement with estimates in the stably-stratified atmospheric boundary layer (Lozovatsky and Fernando, [2013]).

References:

J. M. Klymak and J. N. Moum and J. D. Nash and E. Kunze and J. B. Girton and G. S. Carter and C. M. Lee and T. B. Sanford and M. C. Gregg (2006), An estimate of tidal energy lost to turbulence at the Hawaiian Ridge, J. Phys. Oceanogr., 36, 1148 1164, 10.1175/JPO2885.1.

Lozovatsky, I. D., and H. J. S. Fernando (2013), Mixing efficiency in natural flows, Phil. Trans. R. Soc. A, 371, L11605, 10.1029/2006GL025851.

Ray, R. D. and G. T. Mitchum (1997), Surface manifestation of internal tides in the deep ocean. Observations from altimetry and island gauges, Prog. Oceanogr., 40, 135-162, 10.1016/S0079-6611(97)00025-6.
van Haren, H. (2006), Nonlinear motions at the internal tide source, Geophys. Res. Lett., 33, L11605, 10.1029/2006GL025851.

*Speaker
†Corresponding author: kraig@coast.ucsd.edu

Is the abyssal overturning driven by breaking internal waves?

Casimir De Lavergne * [1], Gurvan Madec [2], Julien Le Sommer , George Nurser , Alberto Naveira Garabato

[1] Laboratoire d'Océanographie et du Climat : Expérimentations et Approches Numériques (LOCEAN) – Museum National d'Histoire Naturelle, INSU, CNRS : UMR7159, Université Pierre et Marie Curie - Paris VI – case 100 4 place jussieu 75252 PARIS CEDEX 05, France

[2] Laboratoire d'Océanographie et du Climat : Expérimentations et Approches Numériques (LOCEAN) – Museum National d'Histoire Naturelle : USM402, INSU, CNRS : UMR7159, Université Pierre et Marie Curie - Paris VI – case 100 4 place jussieu 75252 PARIS CEDEX 05, France

At steady state, Antarctic Bottom Water (AABW) must be consumed in the ocean interior at the same rate it is produced around Antarctica. To understand how and where this consumption is achieved, we estimate deep water mass transformation by internal wave-driven mixing and geothermal heating. Using parameterizations of lee wave and internal tide energy dissipation combined with two different models for the mixing efficiency, we show that near-field mixing by breaking internal tides and lee waves cannot account for the full strength of the abyssal overturning, inducing only _˜ 4 Sv of AABW upwelling north of 30ºS. This is comparable to the _˜ 5 Sv of AABW upwelling caused by geothermal heating. The possible role of remotely-dissipating internal tides in complementing AABW consumption is explored.

*Speaker

Temperature statistics above a deep-ocean sloping boundary: scale separation of internal waves and turbulence

Andrea Cimatoribus* [1], Hans Van Haren † [1]

[1] Royal Netherlands Institute for Sea Research -NIOZ (NETHERLANDS) – Netherlands

A detailed analysis of the statistics of temperature in an oceanographic observational dataset is presented. The data is collected using a moored array of 144 thermistors, 100 m tall, deployed above the slopes of a seamount in the North Eastern Atlantic Ocean from April to August 2013. The thermistors are built in-house at the Royal NIOZ, and provide a precision better than 1 mK and very low noise levels. The thermistors measure temperature every second, synchronised throughout the moored array. The thermistor array ends 5 m above the bottom, and no bottom mixed layer is visible in the data, indicating that restratification is constantly occurring and that the mixed layer is either absent or very thin. Intense internal wave and turbulence activity is observed.

We compute the statistical moments (generalised structure functions) of order up to 10 of the distributions of temperature increments. The statistics are strongly modulated by the tidal phase (warming, cooling), and to a lesser extent by the height above the bottom. The results suggest that internal waves in this data set, while being strongly non-linear and continuously breaking, have quasi-Gaussian statistics. The generalised structure functions show a scaling behaviour for both "small scale" (turbulent) and "large scale" (internal wave) motions. The scaling exponent, however, is different. More interestingly, the transition between these two scaling regimes is abrupt for high order moments, i.e. a scaling break is present in the high order strutcture functions. We suggest that this abrupt break in the scaling behaviour is connected with the buoyancy length (velocity scale over buoyancy frequency). The fact that a sharp break is visible only in the high-order moments, at least in this data set, probably results from the fact that the buoyancy length is relevant only for turbulent motions. On the other hand, internal waves are scale-free, at least according to the dispersion relation from linear theory, and thus have scales both smaller and larger than the break. Since waves are less effective than turbulent motions at producing sharp gradients, their signature on higher order moments is smaller than for turbulent fluctuations, and thus smooth the transition between the two regimes only in the lower order moments. The possibility to define a (state-dependent) scale separation between waves and turbulence may have important practical applications, e.g._˜for LES modelling.

*Corresponding author: Andrea.Cimatoribus@nioz.nl
†Speaker

Internal waves : in the atmosphere

Atmospheric gravity waves: Challenges and steps towards possible solutions

Ulrich Achatz * [1]

[1] Goethe-University Frankfurt am Main – Grüneburgplatz 1 60323 Frankfurt am Main, Germany

A major source of uncertainty in current climate-chemistry models are internal gravity waves (GWs), represented by oversimplified parameterizations (e.g. Fritts and Alexander 2003). The presentation will discuss some central questions to be addressed, and some interesting respective results. One focus will be on the theory and numerically stable modelling of the two-way interaction between subgrid-scale waves, either GWs or geostrophic modes, and the resolved flow (e.g. Achatz et al. 2010, Rieper et al. 2013, Muraschko et al. 2015). Another will be on the spontaneous emission of gravity waves from large-scale flow, with a special eye on the reproducibility of this process in the laboratory (e.g. Borchert et al. 2014). This is to feed into the work of a German/Swiss research unit on the multiscale dynamics of GWs (MS-GWaves, https://ms-gwaves.iau.uni-frankfurt.de/index.php) where explicit models of GW excitation, propagation, and dissipation are to be formulated in a physically and mathematically consistent way, and where these will be tested by implementation into a state-of-the-art numerical-weather-prediction and climate model, and by reference to data from dedicated measurement campaigns and laboratory experiments.

References

Achatz, U., Klein, R.,Senf, F., 2010: Gravity waves, scale asymptotics and the pseudo-incompressible equations. *J. Fluid Mech.*, 663, 120-147

Borchert, S., U. Achatz and M.D. Fruman, 2014: Gravity Wave Emission in an Atmosphere-like Configuration of the Differentially Heated Rotating Annulus Experiment. *J. Fluid Mech.*, 758, 287-311

Fritts, D. C., and M. J. Alexander, 2003: Gravity wave dynamics and effects in the middle atmosphere. *Rev. Geophys.*, 41, 1003

Muraschko, J. , Fruman, M. D. , Achatz, U. , Hickel, S., and Y. Toledo, 2015: On the application of WKB theory for the simulation of the weakly nonlinear dynamics of gravity waves. *Q. J. Roy. Meteorol. Soc.*, 141, 676–697

Rieper, F., Achatz, U. und Klein, R., 2013: Range of validity of an extended WKB theory for atmospheric gravity waves: one-dimensional and two-dimensional case. *J. Fluid Mech.*, 729, 330-363

*Speaker

Gravity-wave induced rotors

Dieter Etling * [1], Christoph Knigge [1]

[1] Institute of Meteorology and Climatology, Univerity Hannover, Germany (IMUK) – Herrenhauser Str. 2 30419 Hannover, Germany

One of the main sources of internal gravity waves in the atmosphere is the forcing by airflow over topography (hills, mountains). Depending on the properties of the background flow (temperature- and wind profiles), this type of forcing leads to two types of waves: evanescent waves and trapped waves. The former travel throughout the troposphere and can even reach the stratosphere, where they can influence the large scale flow e.g. by wave breaking. The latter phenomenon also induces severe turbulence which can be hazardous for air traffic . The other type of waves are trapped in the lower atmosphere between the ground and a few kilometres aloft and are called lee waves. As these waves are bounded by the ground the are interacting with the atmospheric boundary layer, which is dominated by turbulent friction. The main phenomenon induced by the interaction of lee waves and the atmospheric boundary layer are so-called rotors, horizontal vortex rolls located beneath the wave crests. In contrast to the very smooth flow within lee waves , the rotor flow is very turbulent and can be also a hazard for aviation in mountainous terrain. For the latter reason, there have been intensive research activities on rotors by means of large field experiments like T-REX (Grubisic et al., 2008) and high resolution numerical simulations (e.g. Vosper, 2004; Smith and Skyllingstadt, 2009) in the last decade.
Here we contribute to the rotor problem by laboratory experiments performed in the large stratified towing tank at Meteo-France in Toulouse and supplemental numerical simulations by a Large-Eddy-Simulation model. (Knigge et al., 2010, Knigge, 2012). These experiments were performed for some idealized situations with respect to the environmental flow, where the main focus was on the influence of an inversion at top of the atmospheric boundary layer. The results provided an regime diagram for the formation of rotors quite similar to the investigations by Vosper (2004). In combination with the LES simulations some typical characteristics of the rotor flow (e.g. dimensions, velocity fields, turbulence) have been obtained and compared to recent field observations on rotors. As experienced by glider pilots since a long time, rotors can be almost found every time under the wave crests between the surface and boundary layer height (see e.g. Etling, 2014). Hence they constitute a hazard to low level aviation close to mountains.

Etling, D. (2014): Atmospheric gravity waves and soaring flight: Physical principles and practical applications. 104 pp., as e-book freely available under www.schwerewelle.de.
Grubicics, V. and 14 Coauthors (2008): Bull.Am.Met.Soc. 89, 1513-1533.
Knigge, C. (2012): PhD thesis (in German), 155 pp, University Hannover, Germany.
Knigge. C., Etling, D., Paci, A. and O. Eiff (2010): . Q.J.Roy.Met.Soc.136, 442-450.
Smith, C.D. and E.D. Skyllingstad (2009): J.Atmos.Sci., 66, 3147-3164.
Vosper, S. (2004): Q.J.Roy.Met.Soc., 130, 1723-1748

*Speaker

Comparison of Gravity Waves in the Southern Hemisphere Derived from Balloon Observations and the ECMWF Analyses

Valerian Jewtoukoff * , Riwal Plougonven [1], Albert Hertzog , Francois Lott [2], Alvaro De La Camara [2]

[1] Laboratoire de Météorologie Dynamique (LMD) – Polytechnique - X – LMD Ecole Polytechnique, Route de Saclay, 91128 Palaiseau cedex, France
[2] LMD – CNRS : UMR8539 – France

The increase of spatial resolution allows the ECMWF operational model to explicitly resolve a significant portion of the atmospheric gravity wave (GW) field, but the realism of the simulated GW field in the ECMWF analyses still needs to be precisely evaluated. Here the authors use data collected during the Concordiasi stratospheric balloon campaign to assess the representation of GWs in the ECMWF analyses over Antarctica and the Southern Ocean in spring 2010. The authors first compare the balloonborne GW momentum fluxes with those in ECMWF analyses throughout the campaign and find a correct agreement of the geographical and seasonal patterns. However, the authors also note that ECMWF analyses generally underestimate the balloon fluxes by a factor of 5, which may be essentially due to the spatial truncation of the ECMWF model. In- termittency of wave activity in the analyses and observations are found comparable. These results are confirmed on two case studies dealing with orographic and nonorographic waves, which thus supports that the ECMWF analyses can be used to study the geographical and seasonal distribution of GW momentum fluxes. The authors then used both datasets to provide insights on the missing GW drag at 60°S in general circulation models in the Southern Hemisphere spring. These datasets suggest that a significant part of the missing drag may be associated with nonorographic GWs generated by weather systems above the Southern Ocean.

*Speaker

Large-scale atmospheric gravity waves in the Red Sea: SAR contributions to an unfolding mystery

Jorge Magalhaes *† [1], Jose Dasilva [2], Isabel Araujo [3], Roger Grimshaw [4], Jesus Pineda [5]

[1] University of Porto (Porto, Portugal) (U.PORTO) – Departamento de Geociências, Ambiente e Ordenamento do Território – FCUP Rua do Campo Alegre, 687 - 4169-007, Porto, Portugal., Portugal
[2] University of Porto – Portugal
[3] CIMAR/CIIMAR – Interdisciplinary Centre of Marine and Environmental Research – Portugal
[4] Loughborough University – United Kingdom
[5] Woods Hole Oceanographic Institution (WHOI) – 266 Woods Hole Road Woods Hole, MA 02543-1050, United States

The Red Sea is identified as a new hotspot for large-scale atmospheric gravity waves (AGWs). SAR imagery reveals their 2D structure, while favorable propagation conditions are investigated on a seasonal basis. Using weakly nonlinear long wave theory and the observed characteristic wavelengths we obtain phase speeds which are consistent with those observed and typical for AGWs, with the Korteweg-de Vries theory performing slightly better than Benjamin-Davis-Acrivos-Ono. Satellite data between 1993 and 2008 reveals sea surface signatures consistent with horizontally propagating large-scale internal waves, which cover the entire Red Sea and are more frequently observed between April and September (although they also occur during the rest of the year). Possible generations mechanisms are briefly discussed.

*Speaker
†Corresponding author: jmagalhaes@fc.ul.pt

Atmospheric gravity waves from non-orographic sources in the extratropics

Riwal Plougonven * [1]

[1] Laboratoire de Météorologie Dynamique (LMD) – Polytechnique - X – LMD Ecole Polytechnique, Route de Saclay, 91128 Palaiseau cedex, France

Jets and fronts have long been known from observations to be sources of gravity waves, both in the troposphere and into the lower stratosphere. The mechanisms repsonsible for these waves have remained somewhat elusive. In the past two decades, considerable progress has been made in understanding how balanced motions emit gravity waves. Several mechanisms have been identified analytically and will be reviewed: Lighthill radiation, unbalanced instabilities and transient generation by sheared disturbances. These mechanisms however do not provide an explanation for waves observed or simulated in the vicinity of jet/front systems where the flow is more complex than what is tractable by analytical treatment. Idealized numerical simulations have also been used in theoretical studies of 'spontaneous generation' of gravity waves from jets and fronts. In particular, simulations of dipoles, used as analogs to upper-tropospheric jet streaks, have provided a simple cartoon in which the generation is quantitatively explained. The background flow (including a region of strong winds, and a diffluent jet exit region) is found to play a key role in determining the characteristics of the waves that are emitted. The confrontation of these theoretical results to gravity waves in real atmospheric flows will be discussed based on observations from superpressure balloons and on mesoscale simulations carried out in complement to the balloon campaigns. This comparison reveals some adidtional surprises, emphasizing for instance the role of moisture in the generation of waves from fronts.

*Speaker

Resonant growth of inertial oscillations from lee waves

Chantal Staquet * [1], Pierre Labreuche [1,2], Julien Le Sommer [2]

[1] Laboratoire des écoulements géophysiques et industriels (LEGI) – Université Joseph Fourier - Grenoble I, Institut polytechnique de Grenoble (Grenoble INP), CNRS : UMR5519 – 1025 Rue de la piscine - BP 53 38041 GRENOBLE CEDEX 9, France
[2] Laboratoire de glaciologie et géophysique de l'environnement (LGGE) – CNRS : UMR5183, OSUG, INSU, Université Joseph Fourier - Grenoble I – Domaine Universitaire 54 Rue Molière - BP 96 38402 ST MARTIN D HERES CEDEX, France

Lee waves are internal gravity waves produced by a wind blowing over a mountain. Lee wave motion has been the subject of numerous studies, since the linear theory of Lyra (1943) and Queney (1947) in the simplest two-dimensional case with uniform wind and stratified atmosphere. Nonlinear effects next appeared to have an essential impact on the atmosphere, as wave-induced momentum deposition can strongly affect the local winds and result in long-range transport (of ozone for instance) in the stratosphere. Lee wave motions are therefore an essential component of atmospheric flows.
Lee waves can also be generated in the Southern Ocean by the Antarctic Circumpolar Current, a strong, locally barotropic current that can reach the bottom topography. Nikurashin and Ferrari (2010) proposed from two-dimensional numerical simulations that lee wave-induced momentum deposition may lead to the growth of inertial oscillations through a nonlinear and fundamentally dissipative process. The interaction between the lee waves and the inertial oscillations may in turn promote wave breaking and intensify turbulent kinetic energy dissipation and mixing in the deep ocean.

In the present talk, we shall show that the emergence of inertial oscillations can result from an alternate, non dissipative, mechanism consisting in resonant interactions involving the lee waves. Two-dimensional numerical simulations will also be presented to assess the validity of this result.

*Speaker

The Stratification of the Ocean and Atmosphere

Geoffrey Vallis * [1]

[1] University of Exeter – United Kingdom

Internal waves arise in stratified fluids, In this talk I will discuss the processes that give rise to stratification in the ocean and atmosphere, focussing on the large-scale structure of the two fluid systems.

*Speaker

List of participants

- Achatz Ulrich
- Augier Pierre
- Beckebanze Felix
- Bordois Lucie
- Bos Wouter
- Bouchet Freddy
- Bourgault Daniel
- Bourgault Pascal
- Brouzet Christophe
- Cambon Claude
- Campagne Antoine
- Chassagne Rémi
- Cortet Pierre-Philippe
- Dasilva Jose
- Dauxois Thierry
- De Lavergne Casimir
- Delache Alexandre
- Diamessis Peter
- Dossmann Yvan
- Dunphy Michael
- Ermanyuk Evgeny
- Etling Dieter
- Flor Jan-Bert
- Gostiaux Louis
- Grisouard Nicolas

- Horne Ernesto
- Jacques Vanneste
- Jamshidnia Hamidreza
- Jewtoukoff Valerian
- Joubaud Sylvain
- Koch-Larrouy Ariane
- Le Dizès Stéphane
- Lefauve Adrien
- Maas Leo
- Magalhaes Jorge
- Maurer Paco
- Melet Angelique
- Mercier Matthieu
- Micard Diane
- Nicolas Mordant
- Muller Caroline
- Naveira Garabato Alberto
- Odier Philippe
- Pillet Grimaud
- Plougonven Riwal
- Pollmann Friederike
- Ponte Aurelien
- Raja Keshav
- Renaud Antoine
- Richet Oceane
- Rubinstein Robert
- Shmakova Natalia
- Sommeria Joel
- Staquet Chantal
- Sugimoto Norihiko
- Vallis Geoffrey
- Van Haren Hans

- Van Oers Alexander (sander)
- Venaille Antoine
- Voisin Bruno
- Whitt Daniel
- Wingate Beth
- Winters Kraig

Organizing Committee:

- Louis Gostiaux, LMFA, École Centrale Lyon, France
- Caroline Muller, LadHyX, École Polytechnique, Paris, France
- Antoine Venaille, Physics laboratory, École Normale Supérieure de Lyon, France

Administrative coordinator:

- Fatiha Bouchneb, Physics laboratory, École normale supérieure de Lyon, France

Sponsors :

- **CNRS - Mission pour l'interdisciplinarité** Le défi INPHYNITI soutient des collaborations autour de nouvelles thématiques scientifiques émergentes, fortement interdisciplinaires qui, malgré leurs enjeux scientifiques ne trouvent pas le soutien initial, nécessaire à leur démarrage et à leur renforcement/maturation.

- **Centre Blaise Pascal Centre Blaise Pascal**Le Centre Blaise Pascal est une "maison de la modélisation", un lieu de conférences, de recherche et de formation liées à la modélisation numérique dans tous les domaines scientifiques. Le CBP dispose d'une infrastructure numérique complète (salle de TP, clusters de calcul, serveurs dédiés, forge logicielle, outils de travail collaboratif, etc.), des bureaux et des salles de séminaires et de conférences. La composante conférence et animation scientifique interdisciplinaire assure le contact entre étudiants, ingénieurs et chercheurs lyonnais avec les meilleurs spécialistes nationaux et internationaux.

- **ENS-Lyon** With researchers, professors and students form 65 nationalities on campus, the ENS de Lyon represents world-embracing excellence in higher education and research at the intersection of the Exact Sciences, the Humanities, the Arts and the leading edge of Educational Science. The École normale supérieure de Lyon is a recent institution which has inherited a long tradition. At its creation in 2010 it brought together within a single institution every subject except medicine and law to fulfil the traditional missions of training, research and the diffusion of knowledge through the implementation of a three-pronged strategic axis: interdisciplinarity, internationalization and interaction with society.

- **ERCOFTAC - European Research Community on Flow, Turbulence and Combustion** The ERCOFTAC Association was created as an International Association with Scientific Objectives according to Belgian law in 1988. The main aims of ERCOFTAC are: Promote joint efforts of Research Institutes and Industries who are active in all aspects of Flow, Turbulence and Combustion, with the object of exchanging technical and scientific information concerning basic and applied research, and the development, validation and maintenance of numerical codes and data bases.

- **Centre Henri Bénard** Le Centre Henri Bénard est un Centre Pilote d' ERCOFTAC. Il a pour mission de fédérer la recherche au plan régional (Rhône-Alpes-Auvergne) dans le domaine de la mécanique des fluides, de la turbulence et de la combustion, et de favoriser une collaboration industrie/université ouverte vers l'Europe.

- **FST - Faculté des Sciences et Technologies** La Faculté des Sciences et Technologies est une Unité de Formation et de Recherche (UFR) de l'Université Claude Bernard Lyon 1. Elle regroupe la majorité des acteurs (enseignants-chercheurs, chercheurs, personnels administratifs et techniques) impliqués dans la formation et la recherche en Sciences et Technologies à l'Université.

- **ANR - The French National Research Agency** ANR provides funding for project-based research in all fields of science - for both basic and applied research - to public research organisations and universities, as well as to private companies (including SMEs). Employing a method based on competitive peer reviews compliant with international standards, ANR provides the scientific community with instruments and programmes promoting creativity and openness, and stimulate new ideas and partnerships, particularly between academia and industry.