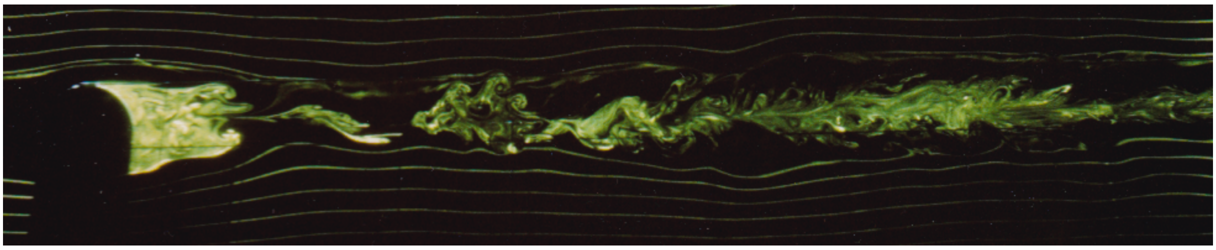

Emil Hopfinger Colloquium 2016

Book of Abstracts

11–13 May 2016
LEGI, Grenoble, France

The EJH Colloquium

Through a career spanning over 50 years of research in fluid mechanics, Prof. Emil J. Hopfinger has made inspiring and renewing contributions to the knowledge of geophysical and industrial flows. In parallel Emil Hopfinger has played a prominent role in the promotion and organization of the engineering community via his involvement in the American Physical Society (APS) in the US, the European Mechanics Society (EUROMECH) in Europe, and the Comité National de la Recherche Scientifique (CoNRS) in France. He has also been active in the creation in Grenoble of the Laboratoire des Écoulements Géophysiques et Industriels (LEGI), which he headed for 5 years.

This three-day Colloquium aims at celebrating Emil Hopfinger's mileage of 50 years of continuing effort in science. It will consist of thematic sessions introduced by plenary survey talks of 40 minutes followed by a small number of regular talks of 20 minutes. The sessions are:

- Environmental flows
  - Stratified flows I Stability and waves
  - Stratified flows II Gravity currents
  - Stratified flows III Turbulence, mixing and waves
  - Convective flows
  - Rotating and turbulent flows
  - Vortex dynamics
- Industrial flows
  - Turbulence
  - Atomization I Drops and bubbles in mixtures, sloshing and surfing
  - Atomization II From shear to filaments, drops and sprays

They will follow a half-day introductory session of reviews on Emil Hopfinger's career, together with Emil's own reminiscence of his career. Attendance for the introductory session is expected large, and smaller for the following sessions, of around 80 participants.

Invited speakers

Bernard Castaing, ENS Lyon & LEGI Grenoble, France
Jean-Marc Chomaz, LadHyX, École Polytechnique, Palaiseau, France
Ross Griffiths, Australian National University, Canberra, Australia
GertJan van Heijst, University of Technology, Eindhoven, The Netherlands
Juan Lasheras, University of California, San Diego, US
Paul Linden, DAMTP, University of Cambridge, UK
Emmanuel Villermaux, IRPHE, Marseille, France

Introductory reviews on Emil Hopfinger's career

GertJan van Heijst, President of EUROMECH
Jacques Magnaudet, President of section 10 of the CoNRS
Paul Linden, APS Fellow & Deputy Editor of the Journal of Fluid Mechanics
Gilbert Binder & Achim Wirth, first and present Directors of LEGI

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Convective flows

Roles of large and small scales in ‘free horizontal convection’

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Recent simulations of Rayleigh-Bénard convection (RBC) show an asymptotic state at $Ra \gg 10^{10}$, in which buoyancy flux is dominated by long-lived, large-scale ‘wind’, which in turn undergoes shear instability leading to production of turbulence. The large scales emerge despite ideal uniform boundary conditions. The turbulence, produced throughout the bulk of the flow, becomes the dominant mechanism for viscous dissipation. Convective flow similar to this in key respects is found above a horizontal plate having an array of many warm and cold patches. This is a form of ‘horizontal convection’ with two of the usual constraints removed: the boundary temperature forcing is no longer one-dimensional nor on the same scale as the domain width, as in all previous studies. Direct Numerical Simulation (DNS) reveals that (even after the system reaches the thermal equilibrium state in which there must be no net heat flux through the boundary and a small statically stable density stratification) there is a full spectrum of scales of motion with an inertial turbulence sub-range. For a deep domain the DNS solutions are dominated by the emergence of domain-scale structures, hence much larger than the scale of the forcing. Laboratory experiments with an array of imposed inputs of freshwater and saline solution through a permeable horizontal base are consistent with the DNS. The convection again reaches a steady state having no net buoyancy flux but clear turbulence spectra, and the flow is again dominated by the domain scale when the fluid depth is sufficiently large. Thus ‘free horizontal convection’ and RBC share the emergence of large scales, which are the most effective for transport of buoyancy, and which also lead to the production of turbulence by shear in the interior.

*Speaker

Transition to geostrophic convection: The role of the boundary conditions

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Rotating Rayleigh–Bénard convection, the flow in a rotating fluid layer heated from below and cooled from above, is used to analyse the transition to the geostrophic regime of thermal convection. In the geostrophic regime, which is of direct relevance to most geo- and astrophysical flows, the system is strongly rotated while maintaining a sufficiently large thermal driving to generate turbulence. We directly simulate the Navier—Stokes equations for two values of the thermal forcing, i.e. $Ra = 10^{10}$ and $Ra = 5 \cdot 10^{10}$, a constant Prandtl number $Pr = 1$, and vary the Ekman number in the range $Ek = 1.3 \cdot 10^{-7}$ to $Ek = 2 \cdot 10^{-6}$ which satisfies both requirements of super-criticality and strong rotation. We focus on the differences between the application of no-slip vs. stress-free boundary conditions on the horizontal plates. The transition is found at roughly the same parameter values for both boundary conditions, i.e. at $Ek \approx 9 \times 10^{-7}$ for $Ra = 1 \times 10^{10}$ and at $Ek \approx 3 \times 10^{-7}$ for $Ra = 5 \times 10^{10}$. However, the transition is gradual and it does not exactly coincide in Ek for different flow indicators. In particular, we report the characteristics of the transitions in the heat transfer scaling laws, the boundary-layer thicknesses, the bulk/boundary-layer distribution of dissipations and the mean temperature gradient in the bulk. The flow phenomenology in the geostrophic regime evolves differently for no-slip and stress-free plates. For stress-free conditions the formation of a large-scale barotropic vortex with associated inverse energy cascade is apparent. For no-slip plates, a turbulent state without large-scale coherent structures is found; the absence of large-scale structure formation is reflected in the energy transfer in the sense that the inverse cascade, present for stress-free boundary conditions, vanishes.

[1] Chandrasekhar, S. 1961 Hydrodynamic and Hydromagnetic Stability. Oxford: Oxford University Press.

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[3] Julien, K., Knobloch, E., Rubio, A. M. & Vasil, G. M. 2012 Heat transport in low-Rossby-number Rayleigh–Bénard convection. Phys. Rev. Lett. 109, 254503.

[4] Kunnen et al. 2016 Transition to geostrophic convection: the role of the boundary conditions. J. Fluid Mech. (to appear).

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Influence of wall roughness and thermal conductivity on turbulent natural convection

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We study turbulent natural convection in enclosures with conjugate heat transfer. The simplest way to increase the heat transfer in this flow is through rough surfaces. In numerical simulations often the constant temperature is assigned on the walls, but this is an unrealistic condition in laboratory experiments. Therefore, in the DNS, to be of help to experimentalists, it is necessary to solve the heat conduction in the solid walls together with the turbulent flow between the hot and the cold wall. Here the cold wall, $0.5h$ tick is smooth, and the hot wall has 2D and 3D rough elements of thickness $0.2h$ above a solid layer $0.3h$ tick. The simulation is performed in a bi-periodic domain $4h$ wide. The Rayleigh number varies from 10^6 to 10^8, two values of the thermal conductivity were chosen, one corresponding to copper and the other ten times higher. It has been found that the Nusselt number behaves as $Nu = \alpha Ra^{\gamma}$, with α increasing with the solid conductivity and it depends of the roughness shape, and 3D elements produce a greater heat transfer than 2D elements. An imprinting of the flow structures on the thermal field inside the walls is observed. The one-dimensional spectra at the center, one decade wide, agree with those of forced isotropic turbulence.

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Atomization I

Drops and bubbles in mixtures, sloshing and surfing

Aiding in the response to the largest marine oil spill disaster ever recorded in history: Flow rate estimation of the amount of oil discharged during the 2010 Deepwater Horizon accident in the Golf of Mexico using statistical correlation algorithms

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The largest marine oil spill in history was caused by an April 20th, 2010 explosion on the *Deepwater Horizon* oil drilling platform located in the Gulf of Mexico approximately 41 miles (66 km) off the coast of Louisiana. The *Deepwater Horizon* sank on April 22, 2010, in water approximately 5,000 feet (1,500 m) deep beginning the uncontrolled discharge for 89 days of an unknown amount of oil. Soon after the accident, the National Incident Command (NIC) chartered the Flow Rate Technical Group (FRTG) to provide scientifically-based information on the discharge rate of oil from the well to assist in the containment efforts and in the allocation of the necessary resources to minimize the environmental impact of the disaster. Using statistical correlation algorithms to analyze video images recorded by remotely controlled underwater vehicles, the FRTG team composed of several former collaborators of Emil Hopfinger, worked for over two months during the disaster to provide the US government with the most accurate estimating of the flow rate of the oil being discharged as well as its dissolution and dispersion in the water column and the amount reaching the surface. In this talk, we will provide a detailed history of the disaster and discuss the methodology used by our group, which included using several models developed by Emil and his former students.

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Parametrically forced axisymmetric gravity waves and jetting in a circular cylinder

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Parametrically forced surface waves commonly known as Faraday waves, can be generated by shaking a container vertically inducing oscillation to the interface of two fluids. The Faraday waves that are sub-harmonically excited have been extensively studied over many decades. Large amplitude gravity waves in axisymmetric and sloshing regime are not yet fully understood. A perfect understanding may facilitate the evaluation of the forces in tank wall and also the heat and mass transfer in liquid propellant tank or other tanks partially filled with liquid experiencing this kind of wave motion. Faraday noticed that the waves formed at the interface have half the forcing frequency. This had been confirmed by the Rayleigh through his experiments. Present work deals with numerical studies of parametrically forced gravity waves in axisymmetric mode in a circular cylinder filled with FC-72 with large liquid depth and compare with the existing results reported in literature.

The computational domain is a cylindrical container of 100mm diameter with FC-72 at bottom and air at top. Moving boundary condition is imposed at the bottom wall and at the wall no slip condition is applied. The simulations have been done in ANSYS 15.0 Fluent using VOF model which helps to track the interface. Both axisymmetric and three dimensional simulations have been carried out for the axisymmetric mode (01) to trace the instability threshold and wave amplitude response. Although three dimensional simulations are performed in the chaotic region and in unstable wave region, validation of axisymmetric simulation for wave breaking and stable wave regions with three dimensional simulations have been done to ensure their axisymmetric nature. The instability thresholds and wave breaking thresholds are plotted from the simulated results which show a good agreement with the reported experimental (Das and Hopfinger 2008) and theoretical results (Hendersen and Miles 1994). When the forcing amplitude crosses the stability threshold, steady state wave amplitude response is observed. Wave amplitude response shows non-axisymmetric behaviour in a small regime below the breaking line and above instability threshold. A notable observation is the presence of different time scales of wave amplitude modulations at different regimes. Wave amplitude modulation exhibits presence of different types of time scales of modulations e.g. slow time scale, period tripling and period quadrupling. In some part of the unstable wave motion (subcritical regime) period tripling (here for amplitude ratio, $A/R = 0.005$, R is the radius of the container) has been observed whereas some part (supercritical regime) shows period quadrupling behaviour (here at $A/R = 0.010$). At higher frequency it bifurcates into a different mode (asymmetric 31 mode). In the overlap region of two, i.e. 01 and 31 modes, there is a small region where coexistence is observed. When forcing amplitude crosses the breaking threshold, wave breaking occurs for axisymmetric mode. In the breaking region, exponential growth of amplitude and subsequent breaking occurs with a high velocity jet ejection from the fluid interface due to the inertial collapse as observed by previous investigators (Zeff et al. 2000 and Das and Hopfinger 2008). Jet formation occurs both with and without bubble pinch-off. From the simulation results it is observed that calculated jet velocity can

*Speaker

be as high as 40 m/s. Zeff et al. (2000) found a jet velocity of 52 m/s with glycerine water solution as working fluid in a slightly larger container.

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Axial sloshing of liquid hydrogen in cylindrical containers with superheated walls in weightlessness

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The most powerful rocket upper stages use liquid oxygen (LOX) as oxidizer and liquid hydrogen (LH2) as propellant. By shutting down the engine, the spacecraft enters microgravity and the fluid free surface is now dominated by capillary forces. Since liquid hydrogen is a perfectly wetting fluid with the contact angle $\gamma_s = 0°$ an axial sloshing motion is initialized.

First technical investigations of the reorientation period were performed by Siegert et al. [1] in the context of the Apollo program in the 1960s. They used a small drop tower to examine the reorientation of different liquids at room temperature, liquid Nitrogen and LH2 ($T_{sat} = 20.3$ K at $p_{sat} = p_0 = 101325$ Pa). In contrast to storable liquids, LH2 is kept under saturation conditions and the surrounding walls are superheated. During the rise at the wall the meniscus travels through a wide range of superheat temperatures and the motion of the meniscus is disturbed by the evaporation and its recoil. The influence of these effects on the sloshing motion of liquid argon and methane was investigated scientifically by Kulev et al. [2,3] and Schmitt and Dreyer [4] using LH2 in the drop tower in Bremen, Germany.

The actual experiments were performed at the same drop tower at the University of Bremen. It provides microgravity for an experiment duration of $t_1 = 4.74$ s with acceleration residuals of $g_{res} < 10^{-5} g_0$ by dropping down an experiment capsule a 110 m tall evacuated drop tube.

The experiment is built up inside a cryostat that contains liquid helium (LHe, $T_{sat} = 4.2$ K at p_0) as coolant and is thermally insulated from the environment by vacuum and multiple radiation shields. The experiment vessel is placed inside this cryostat and is made from glass, which allows an optical observation by an endoscope. Its inner radius is $r = 26.2$ mm, and it is filled with LH2 up to $h = 42$ mm from the bottom. The system is a single species hydrogen system with two phases which is hermetically sealed.

Temperature sensors are bonded to the outside of the cylinder wall to determine the temperature distribution in the height axis. The temperature is regulated by two heating foils on the glass cylinder and the connecting flange respectively. A third heating foil is applied on the bottom of the vessel to manipulate the thermal stratification of the bulk liquid. With exception of the temperature sensors the measuring equipment is assembled outside the cold area.

The influence of two parameters on the sloshing motion and the pressure evolution were investigated, so the temperature gradient at the wall above the free surface $\Delta T/\Delta z = -5$ K/m $\cdots$ 690 K/m and the

*Speaker

temperature difference in the liquid from the free surface to the liquid bulk $\Delta T_{\mathrm{sub}} = 0.12\ \mathrm{K} \cdots 2.24\ \mathrm{K}$.

Three regimes of superheating were identified. In regime A, the liquid and the wall are quasi-isothermal, no nucleation occurs. In regime B, the wall is that much superheated to create nucleate boiling in a retarded manner. This is in contrast to regime C where nucleate boiling occurs immediately after wetting the surface.

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[2] N. Kulev, M. Dreyer, Drop tower experiments on non-isothermal reorientation of cryogenic liquids, Microgravity Sci. Tech. 22, 463–474, 2010.

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Physics of surfing

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Surfing is a cheap and efficient means of transport used by mammals.

But delicate to master.

Catching the wave, finding the equilibrium state and remaining stable are the three main challenges. We address sequentially these problems and focus on the different physical phenomena involved. Identifying the respective role of the slope and of the current is probably the main point of the discussion on catching the wave. For the slope, we will focus on the shoaling effect and show that an analogy with a pendulum provides a way to classify the different types of waves. For the equilibrium we follow Hayes' model for wave riding. Finally, stability is discussed by comparing the stabilizing role of both buoyancy and flow.

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Droplet formation

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I will review studies on atomization starting with the fruitful collaboration with Emil in the early days and ending with recent progres on the 3D Direct Numerical Simulation of the quasi-planar LEGI experiments. Recent comparisons both in 2D and 3D between experiment, theory and simulation will be discussed. It is shown that a linear stability theory, solving the Orr–Sommerfeld equations obtains some success in the comparisons, provided a wake profile is used. The full description of the 3D droplet formation mechanism is still difficult to reach due to the very large range of scales and the complex physics involved.

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On the scaling of jetting from bubble collapse at a liquid surface

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We present a scaling law for the jet velocity from bubble collapse at a liquid surface which brings out the effects of gravity and viscosity. The present experiments in the range of Bond numbers $0.02 < Bo < 2.5$ and Ohnesorge numbers $0.001 < Oh < 0.1$ were motivated by the discrepancy between previous experimental results and numerical simulations. We show here that power law variation of the jet Weber number, $We \sim 1/\sqrt{Bo}$ suggested by Ghabache et al. (2014) is only a good approximation in a limited range of *Bo* values; there is no power law dependency of the jet velocity on *Bo*. The actual dependence of *We* on *Bo* is here shown to be identical to that of the square of the dimensionless cavity depth on *Bo*. Viscosity enters the jet velocity scaling in two ways: (a) through damping of the parasitic capillary waves which merge at the bubble base and weaken the pressure impulse, and (b) through direct viscous damping of the jet formation and the bubble collapse. These damping processes are expressed by a dependence of the jet velocity on *Oh*, from which critical values of *Oh* are given for the onset of jet weakening, the absence of jetting and the absence of jet breakup into droplets.

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Poster session

Temperature fluctuations induced by turbulent dissipation

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In practically every fluid flow, kinetic energy is converted into heat through viscous friction. In a turbulent flow this heat is generated in an inhomogeneous matter and the temperature distribution in the fluid will subsequently not be uniform. We investigate these temperature fluctuations in isotropic turbulence. It is shown by numerical simulations and theory how these fluctuations interact with the turbulent flow that generated them. The intermittent nature of the dissipation rate fluctuations is shown to play a fundamental role in the physics of viscous heating.

*Speaker

Evidence of Görtler vortices in a katabatic jet along a convexly curved slope

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A numerical study of a katabatic jet along a convexly curved slope with a maximum angle of about 35° is considered. The katabatic flow is artificialy generated by ground surface cooling and a stable atmospheric boundary layer with constant stratification is considered as a reference state. Large Eddy Simulation is performed with a special focus on the outer-layer shear of the katabatic jet. A statistical quantitative analysis as well as a qualitative description of vortical structures are used to study the present turbulent flow. It is shown that Görtler vortices oriented in the streamwise downslope direction and with a vertical mushroom shape develop in the shear layer. They play a specific role with respect to local turbulent mixing in the ground surface boundary layer. Prandtl model for katabatic jet is applied to the present results and a revisited version from the litterature is discussed, with an account for specific momentum and heat turbulent diffusion. The vertical and downslope variability of turbulent kinetic energy budget is discussed as well and it is shown that downslope advection and production are far to be negligible in katabatic flows along nonlinear slopes. Such curved slope constitutes a realistic model for alpine orography. The present contribution provides a procedure based on local turbulent anisotropy to track Görtler vortices for in situ measurements, which has never been proposed in the litterature.

*Speaker

Isotropy recovery in rotating–stratified turbulence: the role of Ozmidov and Hopfinger scales

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In rotating–stratified flows, two characteristic time scales, namely the BV frequency N and the Coriolis parameter f, are driving the scale of transition from isotropy to anisotropy in homogeneous turbulence. Introducing the turbulent dissipation rate ϵ, two length scales can be obtained, namely the Ozmidov length scale [1] $L_o = (\epsilon/N^3)^{1/2}$ and the Hopfinger length scale [2] $L_h = (\epsilon/f^3)^{1/2}$. Note that the Hopfinger length scale is often called the Zeman length scale [3], but was first introduced by Mory and Hopfinger in 1985 [2]. L_o and L_h compare the relative effects of inertia and of the buoyancy force or of the Coriolis force respectively, and thus quantify the rise of anisotropy in different scale ranges: at large scales (larger than L_o or L_h) the anisotropy due to strong stratification or strong rotation is dominant, whereas at small scales (smaller than L_o or L_h), universal 3D isotropic characteristics of turbulence appear to be restored.

To confirm directly the role of these two scales, we performed numerical simulations at high resolution (2048^3 points) in freely decaying turbulence at four different stratification rates and six rotating rates. We confirm the role played by L_o and L_h by considering the angular energy spectra. Moreover the two scales are associated to a change of behavior of the poloidal/toroidal components of velocity, linked to Riley's decomposition in wave/vortex mode [4], revisited using its spectral counterpart given by the Craya/Herring frame of reference in Delache et al. [5]. In addition, the latter paper has shown the evidence by DNS of a non-monotonic scale-by-scale distribution of directional anisotropy, from the smallest wave vectors (larger scales) to the Hopfinger threshold wavenumber.

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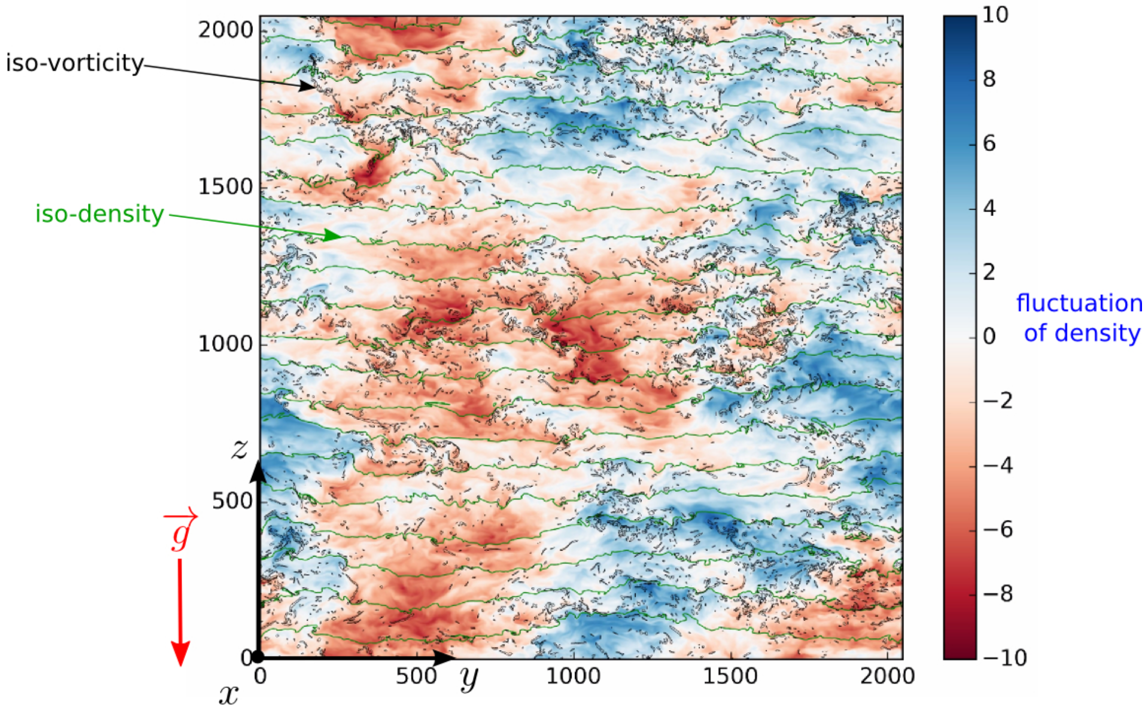
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Kinetic and total mass transfer of a pollutant between two electromagnetically stirred molten layers

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In ladle metallurgical processing, two liquid layers – a metallic layer below a salty or oxide layer – are separated by an interface where mass exchanges occur by the way of a chemical redox reaction. Mass transfers associated with such reaction are strongly dependent on the stirring of each phase as well of their interface.

To work on metal/salt couples of interest to industry, we built a facility to control and measure the full kinetic mass transfer of pollutants from one layer to another. Indeed, by means of induction, a cold crucible reactor can melt, confine and stir, without any physical contact, liquids at very high temperature, with opportunities for continuous treatment.

We use an experimental system able to melt separately metal and salt. Once these elements are molten and brought into contact, a sampling system is used. The experimenter chooses the sampling times. Then, the collected samples and the final metal and salt ingots are analyzed by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) to measure various element concentration During the experiments, both temperature and, intensity and frequency of the inducting current are continuously measured.

In conjunction, a numerical simulation of the experimental reactor is done. We calculate the flows in both salty and metallic layers taking into account of all the present phenomena in each liquid phase (i.e. electromagnetic stirring, buoyancy, turbulence) as well as at the interface (i.e. electromagnetic shaping, viscous shear driving). The implementation of all the couplings needed for a complete simulation is presented. A focus is done on the numerical description of the shear stress near the free interface. Concentrations of the various elements are calculated as post-processing.

Comparisons of experimental and numerically simulated results are done and presenting an excellent agreement.

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How to appear elastic when you are liquid: Emergent mechanical properties of living cells

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Living cells adapt and respond actively to the mechanical properties of their environment. In addition to biochemical mechanotransduction, evidence exists for a purely mechanical sensitivity to the stiffness of the surroundings at the cell-scale. Using a minimal model that describes the collective behaviour of actin, actin crosslinkers and myosin, we show that the mechanosensitive response of cells spreading between distant elastic microplates is entirely and quantitatively predicted by the behaviour of the acto-myosin cortex as a contractile viscoelastic fluid. The result is that a material which is intrinsically liquid has an elastic response to its environement, thanks to the constant influx of biochemical energy.

*Speaker

Atmospheric rotors induced by stably stratified flows over mountains

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When a stably stratified air mass is flowing over obstacles (hills, mountains), the forma- tion of internal gravity waves on the lee side (lee-waves) is often observed. As these waves are bounded by the ground they are interacting with the atmospheric boundary layer, which is dominated by turbulent friction. The main phenomenon induced by theses interactions 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 the terrain-induced rotor experiment (T-REX) in the Sierra Nevada and high resolution numerical simulations in the last decade.

Here we present some results on the rotor problem as obtained by laboratory experiments performed in the large stratified towing tank at Meteo-France in Toulouse. The experiments were performed for some idealized situations with respect to the environmental flow, where the main focus was on the influence of a temperature-inversion in the boundary layer close to the mountain top, which is supposed to be favourable for rotor formation. In combination with the LES simulations, some typical characteristics of the rotor flow (e.g. dimensions, velocity fields, turbulence) have been obtained. As experienced by glider pilots since a long time, rotors can be almost found every time under the wave crests between the surface and the mountain top. Hence they constitute a hazard to low level aviation close to mountains. Therefore the research on atmospheric rotors is not only of scientific interest but has also some practical applications.

*Speaker

Wave and vortex regime in large-gap stratified Taylor–Couette flow

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Stratified Taylor–Couette (TC) flows have been investigated to understand, among others, the equatorial ocean circulation [1,2,3], mixing by vortices [4,5], and in an astrophysical context the stability of accretion disk due to the so-called strato-rotational instability observed experimentally in [6] and first compared to theory in [7]. Here, a centrifugally unstable flow is generated by a cylinder of radius R that is impulsively set into rotation about its vertical axis with angular speed Ω. The gap width is 3 to 13 times larger than the radius of the inner cylinder, and is filled with a linearly stratified fluid with buoyancy frequency N. We are considering the thin vorticity layer at the cylinder boundary of which the dynamics are determined by the Froude number $F = \Omega/N$ and the Reynolds number $Re = \Omega R^2/\nu$, with ν the viscosity. A bifurcation is found at $F = 1$, with for $F > 1$ centrifugally unstable flow with vortices intruding in the ambient stratification, and for $F < 1$, helicoidal inertial waves propagating along the inner cylinder boundary. This bifurcation has also been found in the small gap TC flow in [3,8] though here the waves are unstable and increase in amplitude when the Reynolds number $Re_n = \Omega R^2/(n\nu) > 130$, with n the azimuthal wave mode, and dissipate for $Re_n < 130$. The origin of the instability is discussed.

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*Speaker

Energetic budget of Direct Numerical Simulations in a turbulent stratified flow

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The local mixing produced by turbulence in the ocean interior plays a crucial role in its global energy budget. This mixing drives large scale dynamics, as evidence in the meridional overturning circulation (MOC). The circulation is produced thanks to the downward transport of energy from the surface to the deep bottom of the ocean, possible thanks to vertical mixing. Many processes produce mixing in the ocean. Nevertheless, the proportion of energy transferred from turbulent structures to effective mixing is very difficult to measure in the ocean, and the details of the distribution of the injected energy is yet not fully understood.

In order to answer these questions, a set of 3D Direct Numerical Simulations (DNS) of a turbulent stratified flow are performed by solving Navier-Stokes equation under Boussinesq approximation. A classical Fourier pseudo-spectral method is used with 1024^3 grid points. A porous penalization region is introduced to take into account non-flux conditions at the bottom and at the top of the box, and we assume periodicity in the horizontal plane. A turbulent velocity field is introduced at $t = 0$ which perturbs the initially stable buoyancy profile.

One can distinguish the full buoyancy field associated with the potential energy Ep, and the sorted buoyancy field associated to the background potential energy Eb. The horizontal average of the instantaneous buoyancy field can be used to compute Ep, while the horizontal average of the instantaneous 3D vertically sorted buoyancy field can be used to compute Eb. Ep will contain the energy increase produced by the mixing within the flow in addition to the energy fluctuations associated to the reversible vertical buoyancy flux of waves and overturns. In contrast, the variation Eb is associated only to the irrevesible mixing produced in the flow.

The energetic budget is performed for simulations ranging the Reynolds number between 1000 and 2100 and the Richardson numbers between 3.4 and 14.

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Impact of the valley-wind system on the dispersion of passive tracers in the stably stratified atmosphere of an Alpine valley

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In wintertime, mountain valleys frequently experience very stable atmospheric conditions, leading to air pollution episodes, especially when strong ground-based temperature inversions persist for days. Under such conditions, the valley-wind system (consisting of thermally-driven down-slope and down-valley flows) is key to providing some degree of ventilation. In this study, we analyze results from detailed numerical simulations to quantify the impact of the valley-wind system on the dispersion of passive tracers over an idealized Alpine valley decoupled from the atmosphere above. The numerical simulations were performed using the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem). The down-valley flow extends from the ground surface and the top of the inversion layer and is characterized by a jet-like structure. Tracers emitted at the ground level are trapped below the height of the jet maximum and mixed by shear turbulence within this layer. By contrast, turbulence is generally weak above the jet maximum, and so tracers released there are not mixed in the vertical and are transported down the valley by the down-valley flow. Results show that temporal oscillations of the wind speed within the down-slope and down-valley flows provide a signature of the interactions between the two flows, which affect the tracer concentrations in the along-valley direction.

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Nonlinear reflection of internal gravity waves onto a slope

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The interaction of internal waves on sloping topography is one of the process that cause mixing and transport in oceans. The mixing caused by internal waves is considered to be an important source of energy that is needed to bring back deep, dense water from the abyss to the surface of the ocean, across constant density surfaces. Apart from the vertical transport of heat downwards) and mass (upwards), internal waves are also observed to induce horizontal mass transport through an irreversible mean flow. Mixing and wave induced mean flow may be considered as the processes that transfer wave induced energy to smaller and larger scales respectively. The process of mixing has been a subject of intense research lately. However, the process of wave induced mean flow and their dynamic impact await serious study. The present study involves this wave induced mean flow, its generation and energetics.

The nonlinear subcritical reflection of internal waves from a sloping boundary is studied using laboratory experiments carried out on the Coriolis Platform at Grenoble and, 2D and 3D numerical simulations done using a non-hydrostatic code. In the experiment, a plane wave is produced using a wave generator and is made to reflect normally on a sloping bottom in a uniformly stratified fluid. We consider both rotating and non-rotating cases. The numerical simulation mimicks the laboratory setup with an initial condition of an analytical plane wave solution in a vertical plane limited by a smooth envelope to simulate the finite wave generator.

The nonlinear interaction of the incident and reflected waves produce, apart from higher harmonics, a strong 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. Moreover, 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, its interaction with the wave and account for the loss of wave energy upon reflection.

*Speaker

High Stokes number wave focusing by a circular ridge: Internal, inertial and inertia–gravity waves

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Wave focusing can be considered as a possible scenario for energy concentration in localized zones representing hot spots for incipient overturning in the oceans (Buijsman et al. 2014; Peliz et al. 2009).

In laboratory experiments, internal wave focusing can be produced by horizontal or vertical oscillations of a torus. Ermanyuk et al. (2016) showed that for low Stokes number the wave amplitude increases toward the focal region forming one zone of amplitude amplification. Increasing the oscillation amplitude leads to overturning in this zone. Similarly, experiments in a rotating fluid showed generation of turbulence in the focal zone of inertial waves (Duran-Matute et al. 2013).

The present experiments are performed at the Coriolis platform, 13.5 m in diameter, with a linearly stratified and/or rotating fluid to compare the effects of focusing for internal, inertia–gravity and inertial waves. The waves are generated by a torus ($a = 15$ cm minor radius and $b = 75$ cm major radius) oscillating horizontally with amplitude A. The Stokes number St varies between 3800 and 6800. The angle of propagation θ with the vertical direction is the same for all types of waves. The wave field is measured using PIV.

For large St the structure of the wave beams is bimodal and the focal region is formed of four zones of amplitude amplification. Spectral analysis shows the generation of evanescent higher harmonics close to the torus and in the focal zone. In the presence of rotation, wave energy extends in the vertical direction owing to the generation of columnar vortices. Specifically, horizontal vortices are located in the focal zone for internal waves while for inertial waves they fill the entire domain between the torus and the bottom. The vertical vorticity field of internal waves exhibits a dipolar structure in the focal zone, which transforms in the rotating case, namely for inertia–gravity waves, into a "Yin–Yang-like" structure.

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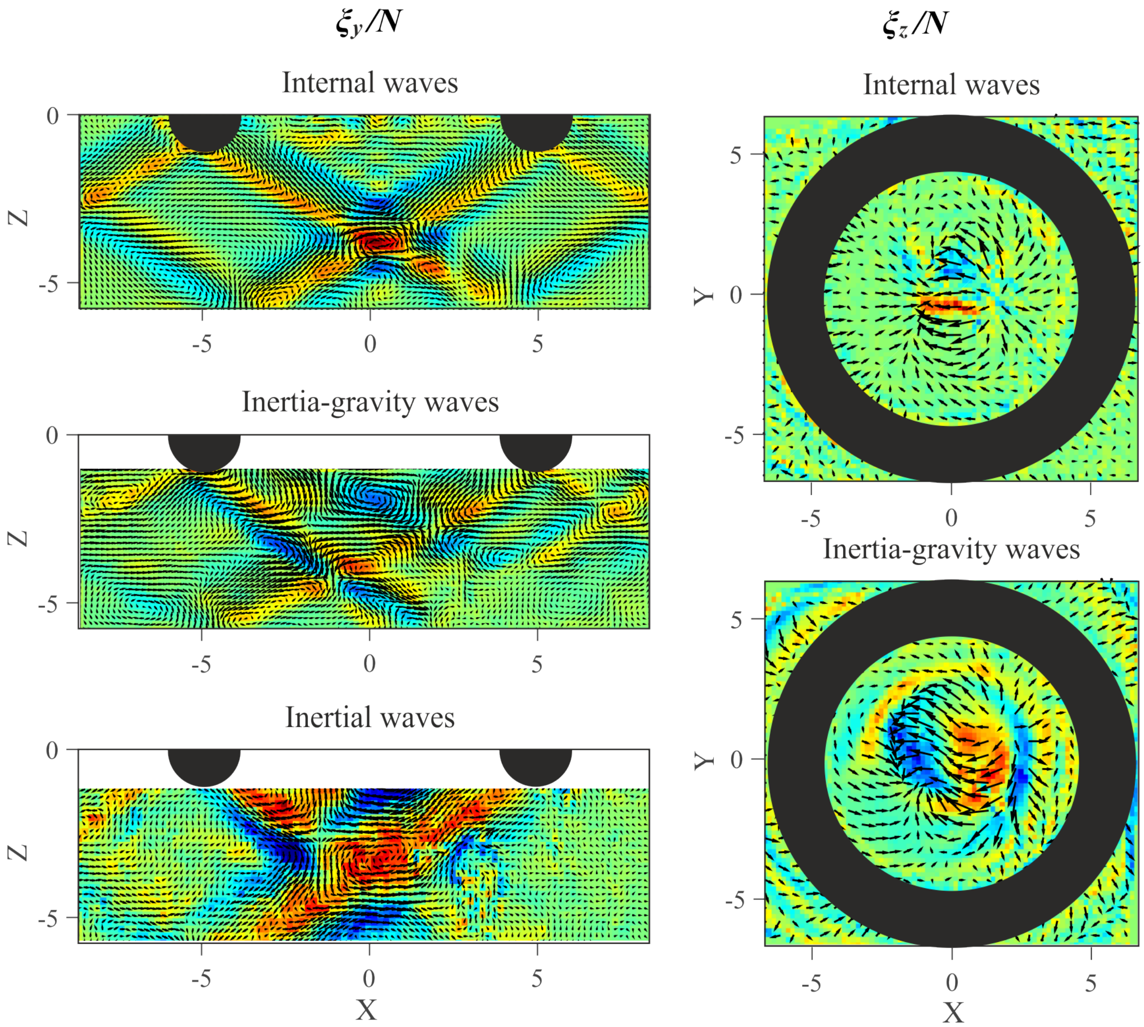

ξ_y/N
ξ_z/N
Internal waves
Inertia-gravity waves
Inertial waves
Z
X
Y
0
-5
5

Modal stability analysis of mechanically-driven flows in rigid rotating ellipsoids

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Because of gravitational torques generated by their orbital partners, most of planets, moons and stars have ellipsoidal shapes and undergo mechanical forcings. It has been proposed that mechanical forcings may be viable alternatives to thermo-chemical convectionas driving mechanisms for planetary dynamos. We investigate the hydrodynamic global stability of incompressible and inviscid fluids enclosed in mechanically forced rigid ellipsoids. We are able to get the growth rate and the velocity structure of any mechanically-driven instability in the linear growth. The method is valid for ellipsoids of arbitrary shape. As examples, stability analysis of libration-driven and precession-driven flows are shown. We predict new domains of instabilities, some of them being valid for laboratory experiments, numerical simulations or planets. Finally, we outline how to use free inertial modes to build weakly non-linear models of any mechanically-driven instability.

*Speaker

Geometric focusing of internal waves – A linear theory

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The conical geometry of three-dimensional monochromatic internal waves gives rise to self-focusing as soon as the wave generator exhibits horizontal curvature. Focusing is all the more pronounced as the generator is close to axisymmetric. A linear theory is proposed for generation by an oscillating circular annulus of vertical axis, with or without azimuthal variations. The theory assumes that the annulus is slender, namely of large aspect ratio, and exploits the associated separation between a local scale at which each cross section interferes only with the opposite section in the same azimuthal plane, and a global scale at which the annulus reduces to a circle. Two annuli are considered, one super-critical (a torus of circular cross section) and the other sub-critical (flat circular Gaussian topography at the ocean bottom). Both complete annuli are considered, and horseshoe-shaped annuli of which one half has been removed either abruptly (for the torus) or through a cosine-squared factor (for the topography). Focusing is observed in all cases, irrespective of criticality or completeness, implying that horizontal curvature is indeed the key ingredient. Good quantitative agreement is obtained for the torus with the laboratory measurements of Ermanyuk, Shmakova & Flór (to be submitted to JFM).

*Speaker

A velocity independent pressure drag for sub-critical two-layer shallow-water flow around an inclined oceanic ridge : A numerical study

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We present results from numerical simulations which show that the pressure drag of a sub-critical two-layer shallow-water flow, in a rotating frame, around an inclined ridge is almost independent of the fluid speed for a large range of Froude numbers. This behavior is observed for barotropic and baroclinic flows approaching the ridge. This result is a counter example to what is actually believed in geophysical fluid dynamics and employed in parameterizations of topographic effects, which are commonly based on a quadratic drag law.

The behavior is explained by the observation that for larger fluid speeds the fluid crosses the ridge at lower depth leading to a shorter path-length. As the frictional head loss is a product of the velocity and the path length, both compensate.

*Speaker

Atomization II

From shear to filaments, drops and sprays

Last but not least: Recollections in the light of new facts on liquid fragmentation

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*Speaker

Primary atomization under the simultaneous action of Rayleigh–Taylor and Kelvin–Helmholtz mechanisms

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The possibility of employing both Rayleigh–Taylor (R–T) and Kelvin–Helmholtz (K–H) mechanisms simultaneously as equal contributors to the primary destabilization process is discussed. A linear stability analysis is performed to develop an understanding of a primary atomization under this combined action. Three-dimensional disturbances are considered in order to predict the breakup structure (ligaments) observed in experiments. The fluids are assumed to be inviscid and incompressible. From the governing equations and the boundary conditions, a dispersion relation is derived and analyzed for a single as well as two interfaces. Four different regimes have been shown to be possible, based on the most unstable axial (k^*) and circumferential (m^*) wavenumbers. They are (i) Taylor mode ($k^* > 0, m^* = 0$), (ii) flute mode ($k^* > 0, m^* > 0$), (iii) sinuous mode ($k^* = 0, m^* = 1$) and (iv) helical mode ($k^* > 0, m^* > 0$). In order to represent the simultaneous action of k^* and m^*, a characteristic length scale ($\mathcal{L}^*$) is defined as $\mathcal{L}^* = \min\left(\frac{2\pi}{k^*}, \frac{2\pi}{m^*}, \frac{2\pi}{k^*m^*}\right)$, where $2\pi/k^*$ and $2\pi/m^*$ represent the two–dimensional length scales in the Taylor and flute modes respectively. The helical mode is represented by a scale given by $2\pi/k^*m^*$. This definition of $\mathcal{L}^*$ allows us to compare the deformation length scales in the three regimes, viz. Taylor, flute and helical mode using a single length scale measure. The dimensionless quantities relevant to this study are Bond number (Bo) representing the ratio of radial acceleration force to the surface tension force and Weber number (We) representing the ratio of the aerodynamic force due to the relative velocity to the surface tension force at each interface.

This study reveals that three-dimensional disturbances (helical modes) dominate the system behavior under certain parametric conditions, which is advantageous to interface distortion. In addition, this study also reveals that for a given energy, the length scale associated with destabilization due to radial acceleration (R–T mechanism) is significantly more efficient than the traditional way of destabilizing an interface using axial relative velocity (K–H mechanism).

In conclusion, the results of our study open up new avenues for designing atomizers to destabilize a liquid sheet by radial motion instead of axial motion. In addition, the onset of transition from absolute instability to convective instability, in the (Bo–We) space is identified.

*Speaker

Flow characteristics and turbulence analysis of a large-scale pressure-atomized spray

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The purpose of this study is to characterize the atomization of a jet of water sprayed into the air at high velocity through a commercial nozzle widely used for sprinkler irrigation. Atomization in sprinkler irrigation is wished to be as gradual as possible. Inefficiency of the atomization process is needed in order that water jets keep a sufficient range to irrigate large areas of farming parcels. As a consequence, the jets involved in sprinkler irrigation are very different from usual sprays. On the contrary to usual liquid sprays, sprinkler jets have a very long core of liquid, which can reach up to 210 nozzle diameters. The surface of this liquid core is very turbulent and on it are present very thin liquid ligaments, which give raise to the first small droplets. Further, the flow is composed of three-dimensional liquid fragments, which are still breaking up and whose surface is very complex. A large variety of scales are present in this flow as the ratio of the large turbulent scales over the smallest liquid length is about 10^4.

The typical diameter of the droplets present in the spray is in the range of several tens of micrometers to several millimeters. They are visualized by ombroscopy. A specific Droplet Tracking Velocimetry (DTV) technique is developed to estimate the size and velocity of these highly polydispersed droplets that are distinctly non spherical. This analysis is performed from the rupture of the liquid core region (distance of about 550 nozzle diameters) to the dispersed zone (distance of about 900 nozzle diameters). With this technique, we obtain joint size-velocity measurements that are rarely produced. Especially two velocity components and also a large diameter range are characterized at the same time; while with other techniques, such as Particle Doppler Anemometry (PDA), the diameter range is quite reduced and requires specific settings. Additional measurements of the liquid volume fraction are performed using a single mode fibre-optic probe. In the light of our experimental data, it appears that the turbulence of the liquid phase in the spray is strongly anisotropic, with the ratio of radial to longitudinal velocity variances which can be as small as 0.1. This ratio (or anisotropy factor) significantly depends on both the droplet size and their circularity parameter R ($R = P^2/4\pi A$ where P denotes the droplet perimeter and A their area, with typically $0.8 < R < 2.2$ on the jet axis). This anisotropy is quite unexpected because other studies on sprays (generally concerned with engine applications) show a relatively low anisotropy. We attribute this increase of anisotropy to the fact that, for this type of spray, the droplet relaxation time is long in comparison to the characteristic time of the turbulence. This strong anisotropy is responsible for the poor radial dispersion of the spray.

*Speaker

Shear instabilities in the context of liquid atomization

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Liquid atomization is the process by which a liquid bulk is fragmented into droplets: in air assisted atomization, efficient droplet break-up is obtained via the destabilization of a slow liquid stream by a fast gas stream (Lasheras & Hopfinger Ann. Rev. Fluid Mech. 2000). There has been a debate over the nature of the shear instability initiating destabilization: is it inviscid, or viscous? We will show that it is actually both. We will next demonstrate that this instability is not only controlled by mean flow features, but also by velocity fluctuations in the gas phase. We will finally discuss more generally how liquid atomization is impacted by large scale motions in the case of air assisted round liquid jets: we will show in particular that the shear instability discussed above is still dominant in controlling large scale motion, and ultimately droplet sizes.

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Vortex dynamics

The anatomy of a draining vortex in a rotating bathtub

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A remarkable feature of the vortex driven by a sink in the bottom of a rotating fluid container is the pronounced upward motion around the fast-rotating cyclonic vortex core with downward motion into the sink. This phenomenon is clearly observed by dye visualisation of the flow near the sink: the flow towards the sink is confined to the Ekman layer at the tank bottom, in which it spirals inwards. Before reaching the sink the fluid first rises to a substantial height, and subsequently flows downwards to the sink in the core of the vortex.

Although this phenomenon has been observed before [1,2], a full explanation was still lacking. We have performed a theoretical analysis of the flow near and in the draining vortex, by distinguishing different dynamical balances at different distances from the sink: a geostrophic potential flow at large distance, and a gradient flow and a cyclostrophic flow balance, respectively, when moving closer to the sink. The theoretical prediction of the flow behaviour in the sink vortex agrees well with the experimental observations.

Additional numerical simulations show very good agreement with the theoretical model.

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Surface and subsurface dynamics of two vortex patches

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Mesoscale and sub-mesoscale processes in the surface ocean layers, on the one hand, play a crucial role in the formation of the basic properties of the water column, and, on the other hand, reflect many dynamic characteristics in the intermediate and deep levels. Thus, the study of the vortex interactions in the surface layers are curious both in themselves, and they are of general theoretical and applied interest.

In this paper, we study the features of the interaction mechanism of two initially circular vortex patches located in the upper layer, basing on a two-layer quasi-geostrophic model. Contour dynamics method allows obtaining numerically diagrams of various states of vortex structures, depending on the upper layer thickness and the Froude number. In particular, in the space of external parameters, we obtained existence domains for a new quasi-stationary state. Its formation scenario is as follows: after a brief merging stage of two vortex patches, a structure of three vortices is formed; further these vortices re-merge, and split again in a cascade way. A final triplet behaves as a stable structure.

We suggest that this kind of vortex triplets is one of an essential attribute of subsurface dynamics of the open ocean.

*Speaker

Self-elongation and nonlinear intensification of unstable baroclinic vortices

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Physical mechanisms of nonlinear evolution of baroclinically unstable circular vortices are analyzed in the context of stratified rotating flows. Development of the most unstable elliptical mode is shown to result in self-elongation of the major vortex core and formation of co-rotating satellites with opposite sign due to splitting of the potential vorticity anomaly in initially quiescent layer into two parts. The role of angular momentum in determining of finite amplitude saturation under the tripolar form is demonstrated using a Hamiltonian model for elliptical vortex core and satellites. Such carousel tripolar flow pattern leads to self-intensification of fluid rotation around the vortex center that has important implications for understanding of the long life of real-ocean eddies.

*Speaker

Production of dissipative vortices by solid boundaries in 2D flows: Comparison between Prandtl, Navier–Stokes and Euler solutions

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Turbulent boundary layers are ubiquitous in geophysical fluid flows and we will study the Reynolds number dependence of the drag due to the interaction between topography and atmospheric flows, or between basins and oceanographic flows. For this we will revisit the problem posed by Euler in 1748, that lead d'Alembert to formulate his paradox and address the following problem: does energy dissipate when a boundary layer detaches from a solid boundary in the vanishing viscosity limit? To trigger detachment we consider a vortex dipole impinging onto a wall and we compare the numerical solutions of the Euler, Prandtl, and Navier-Stokes equations. We observe the formation of a boundary layer whose thickness scales as predicted by Prandtl's 1904 theory. But after a certain time Prandtl's solution becomes singular, while the Navier-Stokes solution collapses down to a much finer thickness. We then observe that the boundary layers rolls up into vortices which detach from the wall and dissipate a finite amount of energy, even in the vanishing viscosity limit, in accordance with Kato's 1984 theorem.

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Turbulence

The Soft to Hard transition in turbulence

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A transition is often invoked, between a low Reynolds number turbulence and the high Reynolds number turbulence (developed turbulence). In shear flows, this transition is called the mixing transition. In Rayleigh–Bénard flows, one can similarly distinguish between soft and hard turbulence. A recent work, concerned with heat pipe flows, shed some light on the nature of this transition. It is the point where the so called inertial range of scales of the developed turbulence appears. The consequence is a drastic change in the relation between heat flux and temperature gradient in the heat pipe.

*Speaker

Closed-loop control of laminar separation bubbles

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Laminar separation bubbles induced by adverse pressure gradients generate in many engineering applications severe losses caused by premature laminar-turbulent transition, pressure drag increase and flow unsteadiness. The mitigation of laminar separation bubbles by flow control remains a highly promising approach. Non-adaptive control, for example by vortex generators, has been used for decades to delay flow separation. Recently Pastoor et al. (2008), Parezanvić et al. (2015) among others, showed the superiority of closed-loop control for drag reduction and increase of mixing. In particular such control systems can adapt to changing flow conditions and external perturbations thus improving the robustness of control. The goal of this study is to apply such closed-loop control to laminar separation bubbles in order to analyse the complex bubble dynamics composed of an intriguing interaction between the Kelvin–Helmholtz instability of the separated shear layer and the flapping motion of the recirculation zone.

Due to real-time constraints most closed-loop systems employ local sensor based feedback with restricted information on the actual flow state. In this study we propose a new global sensor technique based on Lagrangian tracers obtained with the help of the controlled release of hydrogen bubbles in combination with real-time image processing. The experiments are carried out in a low-speed water tunnel with a smooth ramp configuration to generate canonical separation conditions. A vertically movable wire of 0.13 mm thickness (Kaiser et al. 2013) spans over the whole test section upstream of flow separation. This wire works as actuator which is operated by the controller. The actual flow state is evaluated by instantaneous pictures of the tracer distribution. These pictures are analysed by SVD (Singular Value Decomposition) and the corresponding Eigenvalues are supplied to the controller. In this way the actual spatio-temporal scales inside the flow are permanently compared to the control objective function, which targets to minimize the separated flow region. We found that closed-loop control with SVD produces, like the best open-loop reference control, quasi-periodic actuation around the natural frequency of the Kelvin–Helmholtz instability. Similar optimal closed-loop control by quasi-periodic excitation has been found recently for mixing layers and wake flows (Parezanvić et al. 2016). While the separated flow region can be reduced up to 60%, the increase of pressure recovery remains restricted to several per cent. Flow visualisations strongly point to a predicament: while regularly spaced vortices avoid flow separation, they also limit the pressure recovery.

This work has been supported by the ANR SepaCoDe (ANR-11-BS09-018).

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On the near wall dissipation

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Well resolved direct numerical simulations performed in a turbulent channel flow in large computational domains up to the Karman number of 1100 (Bauer et al., Comp. Fluids, 2015), are analyzed in order to revisit the dissipation characteristics near the wall. It is first shown that the axisymmetric homogeneous distributions (form 2) proposed by Georges & Hussein (J. Fluid Mech., 1991) provide a good approximation at all the Reynolds numbers across the whole layer. The local isotropy is never exactly reached but can be supposed to approximately hold only towards the end of the log-layer (precisely at wall distances larger than 300 wall units – wall units are the shear velocity and the viscosity). The data is further analyzed by exploring the dissipation characteristics for fixed amplitudes of fluctuating velocity components in the same way as in Tardu & Bauer (J. Turbulence, 2015) and Tardu (Phys. Fluids, 2016). Contrarily to what has been suggested before, the zero crossings of the *wall normal velocity* v in the *spanwise* direction z *contribute mostly to the dissipation* instead of longitudinal x crossings of the streamwise velocity u (Kailasnath & Sreenivasan, Phys. Fluids, 1993). In the viscous sublayer wherein the dissipation reaches its maximum and where the Reynolds number dependences are much prominent, the contribution of the spanwise zero crossings of v is about 30%, while the contribution of u along x hardly exceeds 5%. One of the most striking results we obtained concerns the mean dissipation conditioned by fixed amplitudes of the spanwise velocity fluctuations w. The mean dissipation condition by fixed w is remarkably constant beyond the viscous sublayer independently of the amplitude of w. This last result indicates different roads to model the dissipation in wall bounded turbulent flows.

*Speaker

Interfacial layers in stratified/non-stratified turbulent flows

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This review connects the concepts of external eddies and wave motions outside stably stratified/non stratified turbulent interfaces interacting with eddy motions within thin layers (with and without shear), and how these flows have been studied in laboratory experiments (including those at Grenoble) and using numerical simulations. The key physical concepts involve eddy blocking and distortion by stratification and shear, and generation of local and distant wave motions. Applications are described to gfd phenomena and turbulent structure.

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Rotating & turbulent flows

The viscous structure of baroclinic critical layers in stratified shear flow with background rotation

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Stratified shear flows with background rotation are known to give rise to the spontaneous replication of zombie vortices when they are subjected to finite-amplitude perturbations. In direct numerical simulations, zombie vortices are produced at baroclinic critical points that are singularities of the underlying inviscid governing equations. In this investigation, a large Reynolds number asymptotic analysis is presented, which regularizes the critical point singularity via momentum and density diffusion within a critical layer of finite thickness. The formulation includes the effects of horizontal shear, stratification and background rotation. The predicted leading-order cross-stream structure in the baroclinic critical layer is shown to agree quantitatively with direct numerical simulations that include the effects of viscosity. The results are compared with those of classical viscous critical layer theory in shear flow instabilities.

PH was supported by a Visiting Professorship from the Miller Institute for Basic Research in Science.

*Speaker

Flow through a rotating, tilted rectangular box

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Laboratory and numerical experiments describe the flow of a homogeneous fluid through a fully-enclosed rectangular box. The flow is driven by an imposed longitudinal pressure gradient of variable strength. The question is raised whether rotation of the system leads to an increase or a decrease of the throughflow. Due to the abrupt way the flow enters and exits the tank, turbulence is created, which, in the rotating case, may manifest itself partly in the form of inertial waves. The energy stored in the inertial wave field is at the expense of that available for the throughflow, especially as the waves will scatter throughout the box and be lost to heat. Hence we expect a decrease of the throughput. However, tilting the box leads to geometric focusing of these inertial waves, that may locally drive a mean flow, amplifying the throughflow. Tilting also allows the presence of topographic Rossby waves, as the fluid column height will then vary. The efficiency of the throughflow will be discussed in relation to the geostrophic balance, obeyed by the mean flow.

*Speaker

Extreme events in turbulent rotating flows: Lagrangian and Eulerian statistics

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Rotating turbulent flows at different Reynolds and Rossby numbers and seeded with millions of particles of different inertia are investigated by direct simulations. We quantitatively show that the deviations from a normal-distribed Eulerian statistics result from the entangled interactions among the structures oriented along the rotation axis and the turbulent background. This happens at rotation rates of practical interest for typical industrial or geophysical application. Concerning inertial particles, we measure the relative importance of Stokes' drag with respect to the Coriolis and Centrifugal forces at different rotation rates and we assess the singular role played by the slow vortical structures to preferentially concentrate (expel) light (heavy) particles, leading to unexpected diffusion properties in the direction parallel (perpendicular) to the rotation axis.

*Speaker

Stratified flows I
Stability and waves

Internal wave in the ocean, local, global stability and transient growth

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Internal gravity waves that exist in a continuously stratified fluid are particularly important in the ocean. They transport energy and are thought to generate turbulent mixing which contributes to the deep ocean circulation. Through fully non-linear and linear direct numerical simulations of the stability of a gravity wave beam, we show that the stability properties and transient growth intensity strongly depend on the mean flow intensity. Small scale instabilities dominate for small mean flow as for internal tide. For lee waves or more generally strong mean flows, large scales lead the instability but small scales dominate the short time growth. Computing the linear impulse response of a monochromatic internal wave we propose an interpretation based on an extension of absolute and convective theory to 2D periodic base flow and make the connection with the classical triadic instability theory of Phillips.

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Energy cascade in internal wave attractors

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One of the pivotal questions in the dynamics of the oceans is related to the cascade of mechanical energy in the abyss and its contribution to mixing. We propose internal wave attractors in the large amplitude regime as a unique experimental and numerical setup that models a cascade of triadic interactions transferring energy from large-scale monochromatic input to multi-scale internal wave motion. Experiments are conducted in a trapezoidal domain filled with uniformly stratified fluid. Fluid motion is measured with conventional PIV and Synthetic Schlieren technique. Numerical calculations are performed with the help of the spectral element method. We discuss the instability scenarios and their relation to the amplitude of the input perturbation and the position of the operating point of the system at zone of existence (Arnold tongue) of a wave attractor. We provide signatures of a discrete wave turbulence framework for internal waves and discuss the statistics of small-scale high-vorticity events, which induce mixing.

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*Speaker

Stratified flows II
Gravity currents

From stratified gravity currents to a practical hydraulic problem

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As an aside in his JFM 1968 article on gravity currents, Brook Benjamin had established the properties of a liquid emptying from a horizontal tube and of the upstream propagation with respect to that liquid of a semi infinite pocket or bubble of air. It turns out that in the hydraulics of pipe flow under gravity a phenomenon is omnipresent which is closely related to Benjamin's idealized model. The latter also informs the mechanics of siphons. Useful but little known practical consequences of this fact have now been exploited.

*Speaker

Energetics of deep Alpine valleys in pooling and draining configurations

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A numerical model is used to investigate the nocturnal atmospheric boundary layer in a valley that opens either on a wider valley (draining configuration) or on a narrower valley (pooling configuration), under decoupled conditions with the free troposphere. One draining case and weak to moderate pooling cases are considered. Numerical results show that the structure of the nocturnal boundary layer is substantially different for the draining and pooling configurations. The greater the pooling, the deeper and colder is the boundary layer. Down-valley winds are weaker for pooling and draining configurations than in an equivalent valley opening directly on a plain, because of the reduction of the along-valley pressure gradient due to the presence of the neighbouring valley. For the moderate pooling case, an up-valley wind develops from the narrower to the wider valley during the evening transition, affecting the mass budget during that period.

Considering the heat budget of the valley system, the contribution of the diabatic processes, when appropriately weighted, hardly varies along the valley axis. Conversely, the contribution of advection with respect to the diabatic processes, varies along the valley axis depending on the configuration: it decreases for a pooling configuration, and increases for a draining configuration. Consequently, for a pooling configuration, the heat transfer between the valley and the plain is reduced, thereby increasing the temperature difference between them. For the moderate pooling case, this temperature difference can be explained by the topographic amplification factor during the early night. This causality holds in a valley when the 'extra' heat loss within the valley due to the surface sensible heat flux balances the heat input due to advection.

*Speaker

Stratified flow near a topographic control

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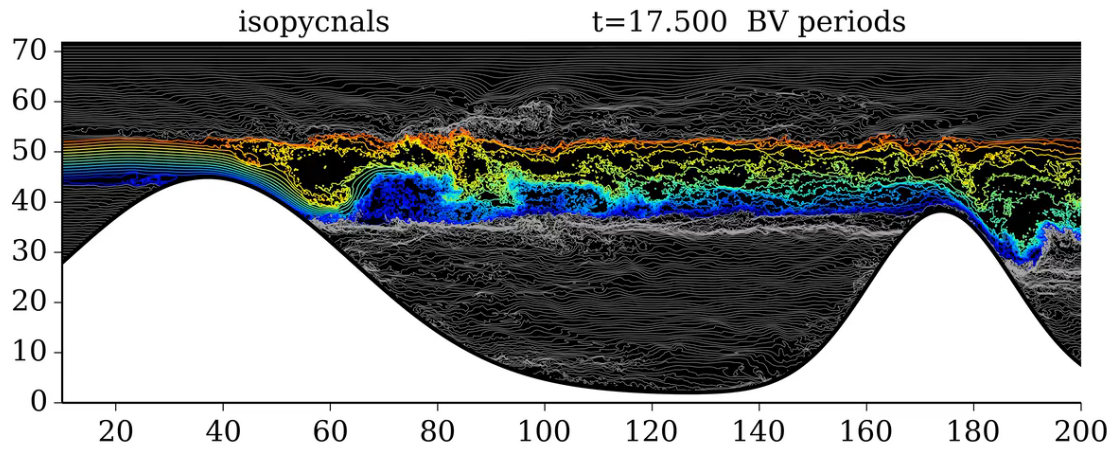
For strongly stratified flows over tall obstacles, i.e. when the topographic *Fr* is small, long internal waves are able to propagate upstream from the obstacle. The upstream influence of these waves leads to blocking and the formation of an upstream jet. The jet becomes hydraulically controlled at the crest of the obstacle and takes the form of an accelerated downslope flow in the lee. In the first half of the talk, an optimal solution for continuously-stratified, topographically controlled flow is derived analytically. This laminar, nonlinear solution describes the upstream flow profile and its transition to a supercritical downslope flow. In the second half of the talk, the fate of the downslope flow, in particular it's separation from the obstacle and its turbulent transition back to a subcritical state are examined. For the same flow conditions upstream and at the crest, the intensity of the turbulence in the lee is shown to depend sensitively on the downstream, subcritical boundary conditions, imposed by specifying the height of a second, downstream obstacle. The blocking height of the downstream obstacle is communicated upstream by internal waves that ride on a sharp pycnocline and set the point at which the downslope flow separates from the upstream obstacle.



*Speaker

Stratified flows III
Turbulence, mixing and waves

The turbulent/non-turbulent interface in a plume

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We present measurements of the scalar and velocity fields of turbulent plumes at high Reynolds and Peclet numbers. We describe how measurements of the movement of identifiable features at the edge of a turbulent plume can be interpreted to determine the properties of the mean flow and consequently, using plume theory, can be used to make estimates of the fluxes of volume (mass), momentum and buoyancy in a plume. This means that video recordings of smoke rising from a chimney or buoyant material from a source on the sea bed can be used to make accurate estimates of the source conditions of the plume. At best we can estimate the volume flux and buoyancy flux to within about 5% and 15% of the actual values, respectively. In addition, we demonstrate that large scale coherent structures at the plume edge form on a scale approximately 40% of the local plume half-width and travel at almost 60% of the average local velocity in the plume.

Particle image velocimetry measurements with simultaneously detection of the scalar edge of a plume demonstrate the significance of engulfment within the process of turbulent entrainment. We show that the vertical mass transport, induced by the plume, within the irrotational ambient environment is a significant portion of the vertical mass transport. This vertical mass transport within the ambient typically occurs in the vertical space between turbulent coherent structures which form at, and are advected along, the plume edge. In such regions, the vertical mass transport outside the plume is approximately 40% of the total mass transport. The vertical momentum imparted on these pockets of ambient fluid enable it to be easily engulfed into the plume.

We argue that turbulent entrainment is initiated by the engulfment of (relatively high momentum) ambient fluid which occurs at the largest scales within the plume. This engulfed fluid is then stretched, and vorticity imparted, at the plume edge; after which, at far smaller scales, irreversible molecular mixing takes place. Hence, unlike a number of studies which conclude 'nibbling' at the interface dominates entrainment, we argue that engulfment should be viewed as the initial stage of the process of turbulent entrainment by plumes. As such, engulfment constitutes a significant, indeed vital, part of turbulent entrainment. These new insights shed light on the process of turbulent entrainment in plumes – insights which we believe hold relevance for the process of turbulent entrainment in other canonical free-shear flows.

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On mixing across a stable density interface

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Stratified turbulent fluids have the propensity to spontaneously form sharp density interfaces. Following the seminal experimental work of Rouse & Dodu (1955) performed in Grenoble, mixing across stable density interfaces has been thoroughly addressed by Emil Hopfinger and collaborators over the last 40 years. This led to a better understanding of what sets the interface shape and the entrainment rate across the interface. We will first review those important contributions, and second present a novel approach to the problem based on a statistical model. Indeed, turbulent mixing in stratified fluids involves a huge number of degrees of freedom, which renders extremely difficult a deterministic approach to the problem. Our model describes the temporal evolution of the probability to measure a given buoyancy level at each height, and accounts for the feedback of buoyancy fluctuations on the mean buoyancy profile. This leads to a hierarchy of subgrid-scale models describing restratification effects and the spontaneous emergence of sharp but finite density interfaces.

*Speaker

Local Thorpe length analysis of a gravity current

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The Thorpe length L_T is an efficient quantity that measures the extent of overturning in stably stratified flows because it only requires a determination of the density field whereas other length scales require information about the velocity field. Thus, L_T is of great interest in oceanography where access to, for example, turbulent energy dissipation is challenging. We use experimental data from a wall-bounded shear flow, similar in nature to an oceanic overflow such as the Mediterranean outflow, to evaluate the stability and mixing characteristics of stably-stratified turbulent shear flows over a range of gradient Richardson number Ri_g from 0.1 to 1. The flow is confined from the top by a transparent horizontal boundary and a lighter fluid is injected into quiescent heavier fluid with relative density difference between 0.0026 and 0.0052. The flow near the boundary is turbulent with a Taylor Reynolds number $R_\lambda \approx 100$, and the density and velocity fields are measured simultaneously using planar laser-induced fluorescence (PLIF) and particle image velocimetry (PIV).

The Thorpe length L_T is the root-mean-square average of Thorpe displacements which are defined as the displacements parallel to gravity necessary to transform a non-monotonic (gravitationally unstable) profile into a monotonic (stable) profile. We evaluate L_T at different downstream positions along the interface between the turbulent current and the quiescent fluid. As Ri_g increases from 0.1 to 1, the interface fraction with non-vanishing L_T, i.e., overturning, varies from near 1 to near 0 and the character of the interfacial instability changes from Kelvin–Helmholtz to Holmboe type. Despite the different nature of the interfacial instability, the probability distribution of the normalized non-zero values of Thorpe length, $(L_T - \langle L_T \rangle)/\sigma(L_T)$ (non-zero average $\langle L_T \rangle$ and standard deviation $\sigma(L_T)$) has universal exponential tails. We also compare the characteristics of L_T with the Ozmidov length L_O and the Ellison length L_E and evaluate the buoyancy Reynolds number Re_b.

*Speaker

Length scales of stratified turbulence: New insight on Thorpe displacements statistics from in situ oceanic measurements and high resolution Direct Numerical Simulations

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The Earth hydrosphere, which is the combined mass of water found on, under, and over the surface of our planet, belongs for 97% in mass to the oceans. Characteristic length scales of anisotropic turbulence, as the Ozmidov scale $L_o = \sqrt{\epsilon/N^3}$ and the Zeman scale $L_z = \sqrt{\epsilon/(2\Omega)^3}$ – first introduced [1] by Mory and Hopfinger in 1985 – are inescapable features for whom is interested in the dynamics of the rotating stratified ocean. More precisely, the estimate the Ozmidov lengthscale is one of the keystones of any vertical turbulent diffusion parametrization, which governs vertical exchanges of heat, salt and nutrients in global oceanic circulation models [2].

Among the candidates for good proxies of the Ozmidov scale L_o, the Thorpe scale L_t, based on adiabatic re-ordering of in situ measured density profiles, is commonly used [3]. Recently, we develepped at the NIOZ accurate (noise level < 0.1mK) temperature sensors which, when stiffly attached to a vertical mooring line, provide high sampling rate (1 Hz) time series of temperature profiles with vertical resolution of $O(1\text{ m})$, over vertical spanning of $O(100\text{ m})$ [4]. If density and temperature are approximately proportional, the Thorpe displacement technique can be used to estimate the temporal and (to some extent) spatial variability of turbulent heat flux in the highly turbulent – but stratified – oceanic bottom boundary layer [5]. As a derivate further estimate, the vertical eddy diffusivity can beestimated as well, however, for the latter one needs a value for the mixing efficiency.

We will present several examples of such measurements, as well as a discussion on the statistical distribution of the Thorpe displacement values (which are positive/negative, and whose rms is the Thorpe scale L_t). These results are compared with the Thorpe displacements computed in high resolution 3D Direct Numerical Simulations, providing a new insight on the characteristic length scale of stratified turbulence.

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*Speaker

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Waves and turbulence in the Southern Ocean: Small-scale processes with global impacts

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The transport of heat, carbon and other properties by the overturning circulation of the Southern Ocean plays a central role in the global climate system. Observation of high rates of turbulent dissipation above regions rough bathymetry led to the hypothesis that turbulent mixing mediated by internal waves is responsible for much of the diapycnal mixing required for the overturning circulation. Many observational studies have estimated the properties of the internal wave field and associated mixing but observations of individual lee waves that can be identified with particular bathymetric features are rare. In this paper we present the first such observations in the Southern Ocean with simultaneous estimates of energy fluxes and mixing. Measurements were obtained from two EM-APEX profiling floats deployed in the Drake Passage during the Diapycnal and Isopycnal Mixing Experiment (DIMES). The floats measured temperature, salinity and horizontal velocity on fine scales and we derived a model of the float motion that enabled the calculation of vertical water velocity from the rate of change of pressure. The observed wave had a vertical displacement over 150 m and velocity fluctuations over $15 \mathrm{cm\,s^{-1}}$ in all three components. The peak vertical flux of horizontal momentum of was $6\ \mathrm{N\,m^{-2}}$, a value that is two orders of magnitude larger than the time mean wind forcing on the Southern Ocean. Turbulent kinetic energy dissipation was estimated using fine-scale parameterisations and found to be elevated above background levels by two orders of magnitude. Comparison will be shown with measurements of lee waves in laboratory studies of stratified rotating flows conducted at the Institut de Mécanique de Grenoble.

*Speaker

Laboratory modelling of momentum transport by internal gravity waves and eddies in the Antarctic circumpolar current

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Wakes in stratified fluids have been an active field of research of Emil Hopfinger (e.g. Hopfinger (1987) – J. Geophys. Research) topics undergoes new developments in the context of the dynamics of the Antarctic Circumpolar current, a strong source of ocean mixing with impact on Earth climate. Recent field campaigns in the Southern Ocean have revealed that the interaction of this current with bottom topography can radiate internal gravity waves whose momentum transport contributes to friction (Naveira-Garabato et al. 2004, Nikurashin & Ferrari 2010). An additional contribution to friction is due the eddy wakes produced behind obstacles. These problems have been much studied in the context of atmospheric dynamics, and several laboratories experiments in a linearly stratified fluid have been performed, for instance Baines (1995), Dalziel et al. (2011). Those previous experiments were however constrained by lateral boundaries and did not reach the fully turbulent regime for the eddy wakes. Moreover the Coriolis effect was not investigated although it is much relevant in the oceanic case due to the small Rossby number.

We have reproduced the wake of a spherical cap in a linearly stratified fluid on the 'Coriolis' rotating platform, 13 m in diameter. A uniform circular current around the tank is produced by a small change of tank rotation speed (spinup) which persists by inertia for the duration of the experiment, typically 15 minutes, over which the flow conditions can be considered quasi-steady with a slow decay by friction. The sphere radius is 80 cm, and the cap height is 20 cm (69 cm in diameter) while the total water depth is 90 cm. The non-rotating case is obtained by introducing a small tank rotation while the water remains at rest by inertia. This is compared to a rotating case with a ratio $f/N = 2.5$ of the Coriolis parameter f to the buoyancy frequency $N = 0.5\ \mathrm{s}^{-1}$. The flow velocity is varied from 3 cm/s to 12 cm/s which allows us to cover the relevant range of Froude numbers. Velocity fields are measured by Particle Imaging Velocimetry in horizontal planes illuminated by a laser sheet.

Confirming a classical result, we find that the lower part of the flow goes around the obstacle, initiating the vortical wake, while the upper part goes above it, initiating the wake of stationary internal waves. These two wakes are visualized in the figure shown, respectively on the left and right hand sides. As expected, the vertical boundary between these two regions is lowered for increasing Froude number, as the flow more easily moves above the topography. We find that the wave part quantitatively compares with the linear theory of Voisin (2007).

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Background rotation change the waves into inertia-gravity regimes and introduce an asymmetry between anticyclonic and cyclonic eddies of the wake. Cyclones organize into coherent vortices. The momentum transport associated with these different features is measured both from local quantities (Reynolds stress and wave flux) and by the global decay of the flow under the effect of topographic drag.

In a second part of the study, still under way, we analyse in a similar way the effect of a pattern of 20 identical caps in an attempt to reproduce the effect of a random topography. The mean current is expected to interact with the waves through a process of excitation of inertial waves by sub-harmonic instability, as obtained in two-dimensional numerical simulations by Labreuche et al. (2015). An alternative mechanism of momentum transport, discussed by Nikurashin et al. (2013), involves the eddies directly generated by the topography and the additional eddies produced by the baroclinic instability of the current vertically sheared by the induced bottom friction. We analyse our results in comparison with both approaches.

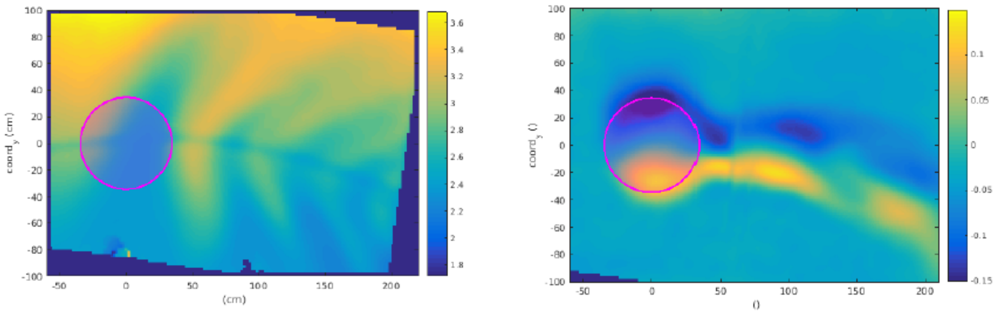

Figure: two horizontal cuts of the wake behind a spherical cap (whose basis is indicated by the circle) in the absence of background rotation: the waves measured at height z=60 cm from the tank bottom (left) and the eddies measured in the lower part at z=10 cm (right). The stream-wise velocity is mapped in the left side view (color scale in cm/s) while the vorticity is mapped in the right side view (color scale in s-1). Both fields are averaged during 1 minute.

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