Workshop on Non-Hydrostatic Ocean Modeling: bridging the gap between sub-mesoscales and boundary layer turbulence

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Modeling internal fine-scale processes in the strait of Gibraltar: a fully 3D non-hydrostatic and non-Boussinesq approach

Lucie Bordois * [1], Francis Auclair [2], Franck Dumas [1], Margaux Hilt [2], Cyril Nguyen [2], Laurent Roblou [2], Yves Soufflet [3]

[1] Service Hydrographique et Océanographique de la Marine – Ministère de la Défense – France
[2] Laboratoire d'aérologie – CNRS : UMR5560, Observatoire Midi-Pyrénées, INSU, Université Paul Sabatier (UPS) - Toulouse III – France
[3] Waves'n See – Société – France

A state-of-the-art non-hydrostatic and non-Boussinesq model (the CROCO ocean community model) was implemented in the scope of realistic 3D Monotone-Integrated Large Eddy Simulation configuration to investigate the dynamics of the internal fine scale processes in the strait of Gibraltar. In this region, steep density gradients, large topographic variations, strong tidal currents (up to 1.8 m/s above Camarinal sill, within the strait) lead to complex generation mechanisms of energetic non-linear and non-hydrostatic internal waves (Farmer and Armi 1988, Vázquez et al., 2006; Vlasenko et al., 2009, Sanchez-Garrido et al., 2011). This tight dynamical equilibrium makes these hydrodynamical regimes a very good and relevant test-case to experience a Non-Boussinesq numerical capability. Besides this technical aspect, it raises many still rather open questions about the physics that impact the ocean dynamics in that region.
The first point is focused on the generation mechanisms. During strong tidal outflow (toward the Atlantic Ocean), the current over the Camarinal sill (CS) is supercritical and large hydraulic jumps are formed (Figure 1). The surface signatures of these hydraulic jumps have been observed using Synthetic Aperture Radar (SAR), which captures variations in surface water roughness and using high-spatial-resolution optical remote sensing images. We investigated the modulation of this process (and its surface signature) according to the tidal intensity all along a neap-spring cycle.

The second point deals with the propagation step. When the tidal ouflow slackens, large travelling internal bores are released over CS; they radiate eastward towards the Tarifa Narrows (TN), steepen and degenerate into periodic solitary wave trains. The way the wave train propagate and even its composition and organization is analyzed especially regarding its phasis within the neap-spring cycles but also regarding the small scale processes like tidal eddies that influence their structure.
These local fine scale processes are driving turbulence levels one order of magnitude larger than those meet in the open-ocean (peak dissipation rates exceeding 10–2 W.kg–1, Wesson and Gregg, 1994). They are thus inducing mixing and likely driving water-mass exchange between the Mediterranean basin and the north-eastern Atlantic in a manner that have to be unraveled.

*Speaker

The interplays of these processes with the vertical mixing and the local circulation are still an ongoing methodological (how the mixing may be quantified) and scientific issue. We will point out some high mixing mechanisms that might be of primary interest during the generation step and which require more thorough investigation.

Non-hydrostatic Dynamics of Freshwater Lenses in the Near-Surface Layer of the Ocean

Cayla Dean * [1], Alexander Soloviev [1]

[1] Nova Southeastern University – United States

Convective rains and/or river runoff produce localized freshwater lenses. The freshwater lenses create significant density anomalies and thus horizontal pressure gradients in the near-surface layer of the ocean. As a result, these lenses can spread and propagate as gravity currents, interacting with wind stress. We have modeled freshwater lens dynamics in the near-surface layer of the ocean using computational fluid dynamics (CFD) tools. We are able to reproduce generic features of the lens spreading and interaction with wind using a 3D CFD model developed with ANSYS Fluent software. The model set up includes an initial 0.5 psu salinity and 0.8 deg C temperature anomaly with a 50 m radius. The wind stress corresponding to $U10 = 8$ m/s is applied to the water surface. The freshwater lens spread as a gravity current, producing a typical gravity current "head". There is some asymmetry of the lens edges due to the effect of the wind. An interesting phenomenon is the development of coherent structures at the frontal edge of the spreading freshwater lens, which apparently intensifies mixing. These structures resemble a complex pattern of three-dimensional water flow motions in the leading edge of the gravity current and trailing fluid, previously reported by Özgökmen et al. (2004) and Soloviev et al. (2015). The model is consistent with measurements conducted as a part of the Gulf of Mexico Research Initiative Consortium for Advanced Research on Transport of Hydrocarbons in the Environment. These results have a number of practical applications including pollution propagation in coastal waters (e.g., oil spills), open ocean dynamics (e.g., Madden-Julian Oscillation), and interpretation of Aquarius and SMOS sea surface salinity satellite measurements.

*Speaker

Implications of Relaxing the Traditional Approximation for Equatorial Waves

Bertrand Delorme * [1], Leif Thomas [1]

[1] Stanford University – United States

Recent observations of small-scale turbulence obtained in the eastern equatorial Pacific show evidence of intense abyssal mixing over smooth topography. It has been hypothesized that the intense mixing could have been driven by surface-generated equatorial waves as a result of the horizontal component of the Coriolis parameter, fh, and weak abyssal stratification. In this work, we test this hypothesis by using nonlinear numerical simulations that allows for non-zero fh. In our simulations, Equatorially Trapped Waves (ETW) are generated in the upper water column and propagate freely into the weakly stratified abyss where the effects of fh are most strongly felt. At these depths, the ETW act to generate Inertial-Gravity Waves (IGW) through near-critical reflection. These non-traditional effects trigger the formation of sharp beams and lead to enhanced shear in the abyss, and subsequent low Richardson numbers, and are more prominent at the inertial latitude.

*Speaker

Non-Hydrostatic Multiphase Modeling

William Dewar * [1]

[1] Florida State University – United States

An area of growing interest in physical oceanographic modeling involves the behavior of mixtures of more than one material. A well known example is the 2010 Deep Water Horizon oil well event, where oil and gas vented into the deep Gulf of Mexico for 87 days. Other examples include modeling of CO2 sequestration in the deep ocean, the behavior of plastic pollutants in the near surface ocean and resuspension of sediments in coastal and near shore flows. This talk will focus on the development and application of a multiphase model that fits within the framework of a single phase Boussinesq fluid. The model will be applied to the Deep Water Horizon event which, when analyzed, stands as an unprecedented ocean convection problem, and therefore as decidedly non-hydrostatic. Amongst the interesting and unexpected results to emerge are the dominant role played by rotation in the plume dynamics and control of entrainment in the plume by plume dynamics.

*Speaker

Weakly nonhydrostatic ocean modeling with hybrid vertical coordinates

Oliver Fringer * [1]

[1] Dept. of Civil and Environmental Engineering, Stanford University – United States

While small-scale processes such as turbulent eddies, convective overturns, and internal wave breaking are strongly nonhydrostatic, such processes will likely not be resolved in large-scale ocean modeling in the next few decades. However, large-scale ocean models can already resolve scales at which processes transition from being hydrostatic to weakly nonhydrostatic. At these scales, a departure from the hydrostatic balance produces a higher-order balance between nonhydrostatic pressure gradients and unsteadiness or weakly nonlinear effects. As an example, internal solitary waves arise from a balance between weakly nonlinear internal wave overturning and nonhydrostatic dispersion. Similarly, internal lee waves generated over short wavelength topography produce a balance between weakly nonlinear momentum advection and vertical nonhydrostatic pressure gradients. Understanding the dynamics of these flows is an important component of designing nonhydrostatic models because they can give insight into minimum grid resolution requirements needed to resolve these dynamics. For example, leading-order internal solitary wave dynamics are resolved when the horizontal grid spacing is smaller than the mixed-layer depth, which gives an upper bound for the grid spacing needed to resolve the weakly nonhydrostatic effects. While this bound provides an indication of the minimum computational cost to resolve such waves, the cost is still exceedingly high for practical simulations in large-scale ocean models. In this presentation, I will go over some numerical experiments demonstrating weakly nonhydrostatic effects in several ocean processes and use these experiments to understand grid resolution requirements needed to resolve those processes. I will also discuss ongoing development of a nonhydrostatic model that employs hybrid vertical coordinates which allows resolution of weakly nonhydrostatic processes with fewer grid points in the vertical, thus reducing the computational cost by up to one order of magnitude.

*Speaker

Explicit simulation of deep-water waves and Langmuir circulations

Yasushi Fujiwara * [1], Yutaka Yoshikawa [1], Yoshimasa Matsumura [2]

[1] Graduate School of Science, Kyoto University – Japan
[2] Atmosphere and Ocean Research Institute, The University of Tokyo – Japan

Langmuir circulations, which arise from the interaction between surface waves and sheared current in the oceanic surface boundary layer, are considered to play important roles in air-sea heat/material transport through an enhancement of surface mixing. While wave-averaged equations (e.g., Craik-Leibovich equation) have been widely used to simulate Langmuir circulations, recent advances in numerical models have enabled us to explicitly simulate surface waves and underlying currents. Still, consistency between such simulation results and wave-averaged ones have not been investigated sufficiently.

We performed a wave resolving numerical simulation of wind-driven currents and surface gravity waves using a latest nonhydrostatic free-surface numerical model that can accurately simulate deep-water waves, under a configuration similar to a wave tank with a wave generator in one end. When waves propagate in the same direction as the wind stress, clear features of Langmuir circulations can be seen in the flow. Detailed vorticity analysis reveals that the rectified effects of the wave motion and vorticity fluctuation associated waves result in net torque driving Langmuir circulations. These residual effects can be understood in terms of vorticity kinematics, such as stretching and tilting, acting on mean flow through Reynolds stress. It is confirmed that this torque is well represented with the curl of the vortex force in the Craik-Leibovich equation, demonstrating the validity of wave-averaged form in this particular configuration.

*Speaker

Modeling transport and mixing by internal gravity waves in the Southern Ocean

Cruz Garcia * [1], Chantal Staquet [2], Joel Sommeria [2], Bruno Voisin [2]

[1] Laboratoire des écoulements géophysiques et industriels – Université Grenoble Alpes, CNRS : UMR5519 – France

[2] Laboratoire des écoulements géophysiques et industriels (LEGI) – Université Grenoble Alpes, CNRS : UMR5519 – 1209–1211 Rue de la piscine - BP 53 38041 GRENOBLE CEDEX 9, France

Motivated by numerical modeling and field measurements of the interaction of the Antarctic Circumpolar Current (ACC) with rough topography in the Southern Ocean (Naveira-Garabato et al. 2004, Nikurashin & Ferrari 2010), two-dimensional numerical simulations were carried out by Pierre Labreuche (PhD thesis, 2015) and experimental measurements were performed in 2016 in the Coriolis platform as part of the master's thesis of Adekunle Ajayi. In the latter studies, an idealized configuration was considered, consisting in a mean flow passing over an isolated "mountain" of hemispheric shape.

In the present work, results of 2D and 3D numerical simulations using the model NHM (Non-Hydrostatic Model) developed by Aiki and Yamagata (J. Geophys. Res. 2004) for this idealized configuration are presented. The objective is to have a better understanding (i) of the relative sinks of the energy of the mean flow due to the emission of a lee wave field and to the formation of a wake behind the topography and (ii) on the respective roles of lee wave breaking and the turbulent wake on fluid mixing.

*Speaker

Generation of waves and vortices in the lee of the Charleston Bump

Jonathan Gula * [1], Noé Lahaye [1], Charly De Marez [1], T Blacic

[1] Laboratoire d'Océanographie Physique et Spatiale – Institut de Recherche pour le Développement, Institut français de Recherche pour l'Exploitation de la Mer, Université de Brest, Centre National de la Recherche Scientifique – France

Surface signatures of internal waves are observed in satellite sun-glitter images where the Gulf Stream flows along the U.S. seaboard, in particular above a deep topographic feature called the Charleston Bump. Deep submesoscale lens-shaped features are also captured in seismic images and glider sections of the Gulf Stream front in the lee of the Bump. These features are typical signatures of anticyclonic submesoscale coherent vortices (SCVs). The generation of waves and SCVs is studied using submesoscale resolving realistic simulations. The model reproduces the observed signature of the waves at the surface and SCVs at depth. The SCVs are generated primarily where the Gulf Stream meets the Charleston Bump due to the frictional effects and intense mixing in the wake of the topography. The waves are generated by the interaction of the Gulf Stream with small scale topographic features. These waves are shown to match with the linear theory describing topographically-generated internal waves. The study of the energetic budget highlights that the nonlinearities of lee waves above the Charleston Bump account for significant energy dissipation, corresponding to about 1

*Speaker

Advances in non-Boussinesq CROCO

Patrick Marchesiello * [1], Francis Auclair [2], Rachid Benshila [3], Lucie Bordois [4], Xavier Capet [5], Laurent Debreu [6], Franck Dumas [7], Swen Jullien [8], Jared Penney [9], Laurent Roblou [10]

[1] Laboratoire d´tudes en Géophysique et océanographie spatiales – Institut de recherche pour le développement [IRD] : UMR065 – France
[2] Laboratoire dáérologie - LA – Université Paul Sabatier - Toulouse 3 – France
[3] Laboratoire d'études en géophysique et en océanographie spatiale – Centre National de la Recherche Scientifique - CNRS – France
[4] Service Hydrographique et Océanographique de la Marine (SHOM) – Service Hydrographique et Océanographique de la Marine (SHOM) – France
[5] Laboratoire dÓcéanographie et du Climat : Expérimentations et Approches Numériques – Centre National de la Recherche Scientifique : UMR7159 – France
[6] INRIA-LJK, Grenoble – INRIA Greoble-Rhône Alpes, Univ. Grenoble-Alpes, Laboratoire Jean Kuntzman – France
[7] Service Hydrographique et Océanographique de la Marine (SHOM) – Ministère de la Défense – 13 rue du Chatellier 29200 BREST, France
[8] Laboratoire dÓcéanographie Physique et Spatiale – Institut français de Recherche pour l'Exploitation de la Mer – France
[9] Laboratoire d´tudes en Géophysique et océanographie spatiales – Centre National de la Recherche Scientifique - CNRS – France
[10] Laboratoire dáérologie - LA – Centre National de la Recherche Scientifique - CNRS – France

CROCO (Coastal and Regional Ocean Community model) is a new oceanic modeling system whose kernel is built upon ROMS and SNH non-Boussinesq approach. CROCO is designed for solving fine-scale processes from the regional ocean to littoral zone with capabilities for LES-type simulations in realistic configurations, including coupling with the atmosphere, waves, sediments and ecosystems. Particular attention is given to numerical accuracy, high-performance computing (optimization, scalability), portability and easy access (http://www.croco-ocean.org). This communication first presents a quick overview of non-Boussinesq CROCO. We then discuss the relevant choices of numerical methods from regional to Large Eddy Simulation (LES), and in particular the choice of closure between physical (turbulence closure) and numerical closure (as in iLES). This is illustrated with non-hydrostatic applications ranging from internal to surface gravity waves and micro-turbulence. We will expose some of the model expected capabilities (e.g., nesting between hydrostatic and non-hydrostatic domains) and compare the non-Boussinesq approach with the more traditional anelastic approximation - also implemented in CROCO - where acoustic waves are filtered. The pros and cons can now be more thoroughly investigated within the common framework provided by CROCO.

*Speaker

Diapycnal mixing near topography

Ali Mashayek * [1]

[1] Department of Civil and Environmental Engineering Grantham Institute of Climate Change and the Environment, Imperial College, London – United Kingdom

Diapycnal mixing in vicinity of solid boundaries of the deep ocean have recently been shown to be regions of intense localized upwelling of abyssal waters through mechanisms different from breaking of tidally-induced internal waves. To show this, I will provide results from a series of nested simulations of the Southern Ocean which were designed for, tuned to, and used to interpret results from a major US-UK funded field program. The highest resolution of the simulations is 10m in the vertical and 100m in the horizontal, the latter being limited by resolution of the best available abyssal topographic data. The aspect ratio of the grid cells is 10 and so the simulations are still hydrostatic. The processes of interest require nonhydrostatic modeling and by participating in this workshop I am hoping to get some insight into non-hydrostatic modeling of such processes. I will also highlight the need for studying similar processes in the North Atlantic basin, especially along the western boundary. This will hopefully connect with simulations already performed by some of the other workshop participants.

*Speaker

From Regional Simulations to LES

Jeroen Molemaker * [1,2]

[1] IGPP, UCLA – United States
[2] Laboratoire d'Océanographie Physique et Spatiale – Institut de Recherche pour le Développement, Institut français de Recherche pour l'Exploitation de la Mer, Université de Brest, Centre National de la Recherche Scientifique – France

Not communicated

*Speaker

Dissipation of internal tides in the abyssal ocean: linear and nonlinear processes

Caroline Müller * [1], Oceane Richet [2], Jean-Marc Chomaz [3]

[1] Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure, Paris, France (LMD, ENS) – Ecole Normale Supérieure de Paris - ENS Paris – 24, rue Lhomond 75231 Paris cedex 05, France
[2] laboratoire d'hydrodynamique de l'ecole polytechnique (ladhyx) – Polytechnique - X – France
[3] Laboratoire d'Hydrodynamique (LadHyX) – Ecole Polytechnique – 91128 PALAISEAU CEDEX, France

Internal tides are internal waves generated by the interaction of the barotropic tide with the abyssal sea-floor. Internal waves are ubiquitous in the ocean, and are believed to play an important role in setting the properties of deep-water masses, and thus in the large-scale ocean circulation. Indeed, in the abyssal ocean, observations indicate that diapycnal mixing (mixing across isopycnals) is largely dominated by the breaking of internal waves. These waves transport energy, and when they become unstable and break, dissipate this energy, thereby contributing to mixing oceanic water masses. This mixing is strongly inhomogeneous in space and time, but its distribution remains poorly understood. Uncertainties in the spatial distribution of wave energy dissipation and concomitant diapycnal mixing, limit our ability to understand the ocean global circulation and water mass formation.

In this talk, we will investigate the spatial distribution of the dissipation of internal tides, and of the induced mixing. In a first step, we will use linear theory to estimate the spatial distribution of tidal energy carried by those waves, and to assess the fraction of this energy which is dissipated through wave breaking. In a second step, we will then investigate in detail the nonlinear processes leading to wave instabilities and breaking. Notably, recent numerical studies in idealized settings suggest the existence of a critical latitude (near 30 degrees), where tidal dissipation is enhanced. The existence of this critical latitude has been attributed to the parametric subharmonic instability (PSI). Using high-resolution simulations and theory, we will confirm the importance of triadic resonant instabilities equatorward of the critical latitude, but will also highlight the importance of evanescent waves poleward of the critical latitude. Finally, in a third step, we will assess the robustness of those results in simulations with more realistic settings. We are particularly interested in the impact of a mean current on the latitudinal distribution of tidal mixing and its enhancement at the critical latitude.

*Speaker

Modelling of idealized Kelvin-Helmholtz configurations using CROCO-NH

Jared Penney * [1], Yves Morel [1], Peter Haynes [2], Francis Auclair [3], Cyril Nguyen [3]

[1] Laboratoire d´tudes en Géophysique et océanographie spatiales – Observatoire Midi-Pyrénées, Centre National de la Recherche Scientifique : UMR5566 – France
[2] University of Cambridge – United Kingdom
[3] Laboratoire d'aérologie (LA) – CNRS : UMR5560, Observatoire Midi-Pyrénées, INSU, Université Paul Sabatier (UPS) - Toulouse III – 14 avenue Edouard Belin 31400 Toulouse, France

Stratified shear flows are an integral component of many geophysical fluid systems. It is therefore important to develop a fundamental understanding of how shear flows can redistribute and mix various geophysically relevant tracers (e.g., nutrients, plankton, pollutants). In this talk, we discuss the use of CROCO-NH for the modelling a traditional stratified shear layer configuration leading to Kelvin-Helmholtz instabilities in the presence of passive tracer layers. Tracer redistribution by KH instabilities is profiled using the Winters-D'Asaro-Nakamura turbulent diffusivity formulation and the use of tracer-tracer scatter plots. A method for estimating the effective global diffusion of tracers obeying a typical advection-diffusion equation is presented as a metric of the influence of numeric effects on the strength of diffusion.

*Speaker

LES ocean modeling at LOPS

Jean-Luc Redelsperger * [1]

[1] Laboratoire dÓcéanographie Physique et Spatiale – Centre National de la Recherche Scientifique – France

An ocean model version of the french community non-hydrostatic atmospheric model Meso-NH (Lac et al 2018) has been developed. The main goal is to have an unique code including both ocean and atmospheric models with the ability to directly couple them using same numerical scheme grid and subgrid turbulence parameterization. The LES ocean version will be presented including the 1D and 3D turbulence schemes, grid nesting capabilities and complete budgets of mean and turbulent quantities. To illustrate these latter, examples of deep oceanic convection simulations at O(1m) resolution will be shown. Current developments will be discussed, in particular the coupled ocean-atmosphere LES model and the use of model to evaluate and improve representation of oceanic convection in regional/climate models.

*Speaker

CROCO-NH a non-hydrostatic version of CROCO

Guillaume Roullet * [1]

[1] Laboratoire d'Océanographie Physique et Spatiale – Institut de Recherche pour le Développement, Institut français de Recherche pour l'Exploitation de la Mer, Université de Brest, Centre National de la Recherche Scientifique – France

After an intense development work, the team organizing this workshop, has come up with a full non-hydrostatic version of CROCO, the regional model circulation that builds up on ROMS. I'll present the specifics of this new version, both in terms of physics and numerical choices. A great deal of attention has been put on speed, that should make this NH version a very useful tool study NH flows. This NH version is targeted to be ran on large grids, in realistic configurations. A companion presentation by Molemaker will present first results.

*Speaker

Predictability of ROMS-Ocean State Ocean Model (ROMS-OSOM)

Aakash Sane * [1], Baylor Fox-Kemper [1], Dave Ullman [2], Chris Kincaid [2], Lew Rothstein [2]

[1] Brown University – United States
[2] University of Rhode Island – United States

The Ocean State Ocean Model (OSOM) is an implementation of ROMS with varying resolution on order of 200m in the horizontal and 1m in the vertical simulating the tidal estuarine waterways of Rhode Island and neighboring regions. It includes Narragansett Bay, Mt. Hope Bay, large rivers, and the Rhode Island Sound and continental shelf region between Long Island and the Elizabeth Islands. Overall the region is roughly 400 square kilometers with an average depth near 20m. A variety of environmental and societal challenges are being addressed with a biogeochemical modeling system, but this part of the project focuses on the physical aspects.
We are using concepts from information theory to measure predictability of the OSOM model for various parameters such as temperature, salinity, etc. Predictability gives the measure of the forecasting capabilities of the model. At present, it is clear that there is significantly different predictability for temperature, salinity, and momentum, given the differing sources and inventories of these conserved quantities. Initial conditions are not highly constrained by data, nor are boundary conditions provided from regional climate models error-free. It is our intention to understand the sources of the dominant errors and their impact on forecasts and hindcasts using the model.

It is also clear from this preliminary analysis that the degree of mixing is an important control parameter. Simulations are highly sensitive to choices made in subgrid schemes. Thus, our future plan involves using a higher-resolution ROMS non-hydrostatic version to focus on a small section of the bay as a Large Eddy Simulation, which can be used as a "truth" scenario for improving the subgrid scheme choices in the OSOM.

*Speaker

A Multi-phase Model of the Air-sea Interface under Tropical Cyclone Conditions

Alex Soloviev * [1], Cayla Dean [1], Michael Mcgauley [1]

[1] Nova Southeastern University's Halmos College of Natural Sciences and Oceanography – United States

Some tropical storms undergo dramatic rapid intensification, which may be related to the properties of the air-sea interface under extreme wind speed conditions. The mechanisms that control disruption of the air-sea interface in tropical cyclones are somewhat analogous to the process of atomization in engineering applications, such as fuel injection in combustion and cryogenic rocket engines, food processing, and inkjet printing. The instabilities may include the well-known interfacial mode (Kelvin-Helmholtz instability) and a "liquid" mode (which may have some resemblance to the Holmboe instability). In this work, computational fluid dynamics experiments have been performed using a multi-phase volume of fluid large eddy simulation model (ANSYS Fluent) to reproduce properties of the air-sea interface under tropical cyclone conditions. A very fine resolution mesh 0.75 mm x 0.75 mm x 0.75 mm and a realistic surface tension coefficient (0.072 N/m) were set at the air-water interface. The model was forced with hurricane force wind stress at the top of the air layer. The periodic boundary condition along the wind direction was equivalent to an infinite fetch. The model reveals a noticeable asymmetry between the air and water sides of the interface-most of the action is on the airside. Such asymmetry is typical for the Kelvin-Helmholtz instability at a gas-liquid interface with a significant density difference as previously observed in laboratory experiments. Computational and laboratory experiments have helped to parameterize the air-sea drag coefficient dependence on wind speed that can explain the rapid intensification and rapid decline of tropical cyclones (Soloviev et al. 2017). A volume of fluid to discrete phase model is under development for a more realistic enthalpy exchange parameterization, and the first results will be presented at the Workshop.

Soloviev, A. V., R. Lukas, M. A. Donelan, B. K. Haus, I. Ginis, 2017. Is the state of the air-sea interface a factor in rapid intensification and rapid decline of tropical cyclones? Journal of Geophysical Research - Oceans 122, 10174-10183.

*Speaker

Two-way coupling between a deep-water surface gravity wave and a circulation consisting of a roll circulation and an along-roll jet

Nobuhiro Suzuki * [1]

[1] Laboratoire d'Océanographie Physique et Spatiale – Institut de Recherche pour le Développement, Institut français de Recherche pour l'Exploitation de la Mer, Université de Brest, Centre National de la Recherche Scientifique – France

The interaction between a deep-water wave and a circulation (e.g., Langmuir or frontal circulation) consisting of a roll circulation parallel to the wavenumber and an along-roll jet is crucial to both wave models and wave-averaged circulation models (in which wave oscillations are averaged out and unresolved). Improving our knowledge of this interaction requires proper consideration of (1) the water momentum and pressure at the heights above the wave trough and (2) the significant gradients and vertical velocities of the circulation. To this end, this study develops a theory without ever mapping or extrapolating the water momentum and pressure into the region outside the water. Additionally, the theory does not assume the wave's second-order irrotationality or the current's incompressibility. Then, this study discovers seven types of current-influenced higher-order wave motions. It also determines the influence of the roll circulation on the tendencies of the wave amplitude and wave action density. Using these results, the wave-averaged governing equations are also derived. The derived equations are similar to the Craik-Leibovich (CL) equations but crucially different in two aspects concerning the wave refraction and the governing divergence property for the wave-averaged physics. Unlike the CL equations, this result indicates that, for a given roll circulation and wave slope, a longer wave forces the roll circulation more than a shorter wave. Furthermore, this forcing is weaker than the CL equations and more dependent on both the wavelength and the vertical profile of the along-roll jet.

*Speaker

Eddy strain induced modifications to near-inertial waves and their implications for the energetics of the waves and eddies.

Leif Thomas * [1]

[1] Stanford University – United States

While there have been many studies focused on the modulation of near-inertial waves (NIWs) by vertical vorticity, little attention has been paid to the effects of eddy strain on the waves. Results from hydrostatic simulations of NIWs in a field of eddies will be presented that highlight how eddy strain can intensify vertical radiation of NIW energy out of the upper ocean and drive a transfer of energy from the eddies to the waves. As might be expected, strain leads to an exponential increase in a NIW's horizontal wavenumber. However, the response of the waves to this straining is greatly affected by background lateral density gradients, as the strain also generates fronts and their concomitant ageostrophic secondary circulations (ASC). Geostrophic and ageostrophic shears at fronts modify the properties of the NIWs and produce an anisotropic response. NIWs moving from the light to dense side of a front experience an increase in frequency and rapidly propagate downward, while NIWs traveling in the opposite direction are trapped to the front, remain in the upper ocean, and oscillate at subinertial frequencies. These subinertial waves extract energy from the eddies and thus act to transfer energy from balanced to unbalanced motions. In contrast, the downward propagating waves experience an upward shift in frequency that strengthens with increasing strain. These simulations illustrate how the interaction of eddy strain, fronts, and NIWs can result in a transfer of kinetic energy from the eddies to the waves and frontal ASC, however they are incapable of determining the ultimate fate of this kinetic energy, that is, how it is dissipated or converted to potential energy through mixing. This task will require multiscale non-hydrostatic simulations that simultaneously capture straining by the mesoscale, frontal and NIW physics on the submesoscale, and small-scale turbulence. The objectives and potential designs for such simulations will be discussed.

*Speaker

Finding waves in a sea of eddies: Separating balanced from unbalanced motions in nonhydrostatic simulations

Kraig Winters * [1]

[1] Scripps Institution of Oceanography, UC San Diego – United States

Not available

*Speaker

List of participants

- Ayouche Adam
- Bakhoday Paskyabi Mostafa
- Barkan Roy
- Bordois Lucie
- Buckingham Christian
- Chassignet Eric
- Cimoli Laura
- Couvelard Xavier
- Crystle Greace
- De Marez Charly
- Dean Cayla
- Delorme Bertrand
- Dessert Morgane
- Fujiwara Yasushi
- Garcia Cruz
- Grima Nicolas
- Gula Jonathan
- Jullien Swen
- Lahaye Noé
- Le Sommer Julien
- Marchesiello Patrick
- Mashayek Ali
- Onken Reiner
- Penney Jared
- Prakash Kumar

- Redelsperger Jean-Luc
- Rosa Kevin
- Roullet Guillaume
- Sane Aakash
- Sayol Juan Manuel
- Soloviev Alex
- Srivastava Atul
- Suzuki Nobuhiro
- Tang Qiang
- Tedesco Pauline
- Thomas Leif
- Uchida Takaya
- Van Der Boog Carine
- Vic Clément
- Wienkers Aaron
- Yu Xiaolong