PhD thesis on oceanic convection

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Topic	Observation and parameterization of oceanic convection
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Summary

Oceanic convection remains poorly understood even though it is one of the main driver of the oceanic dynamics. Convection can be penetrative (entrain water from below the mixed layer) or non-penetrative. While it is reasonably straightforward to formulate conceptual parameterizations of non penetrative convection in idealized settings, it remains challenging to extend the formalism to realistic settings of penetrative convection even for state of the art ocean models. In fact the most advanced parameterization schemes for oceanic convection are still calibrated based on atmospheric data. Moreover these parameterizations do not take into account the rotation of the earth which can substantially impact the individual and collective behavior of convective plumes.

The first objective of this PhD thesis is to build an observational database of convective events on the Coriolis Platform (the largest rotating tank of the world). We will complement this dataset with numerical simulations to explore many types of surface forcing and initial conditions. We will then combine these observations and model outputs with a robust theoretical framework to build a consistent parameterization of oceanic convection.

Profile and skills required

This thesis topic is aimed at a student interested in ocean dynamics, in the realization and analysis of laboratory experiments and in the analysis of high resolution simulations. A master's degree in physical oceanography, meteorology, climate science, or geophysical fluid mechanics is required. Knowledge in large database analysis tools (e.g. Python) will be a plus.

Scientific context

The ocean plays a fundamental role in modulating climate change via heat and CO2 sequestration. Heat and CO2 enter in the ocean at the air-sea interface and remain temporarily in the upper part of the ocean (the mixed layer). In the wintertime, cooling and wind trigger convective events which enhance mixing and deepen the mixed layer. During this phase, excess heat and CO2 may be transported into the interior and shielded from further interaction with the atmosphere for years or centuries. Such convective events remain poorly understood even though they act as a key driver of the ocean circulation. The correct parameterization of sub-grid turbulent processes related to ocean convection is a problem of growing concern since climate predictions are often unreliable when convective processes are not correctly included in ocean models (Huang et al. 2014; Koenigk et al. 2021).

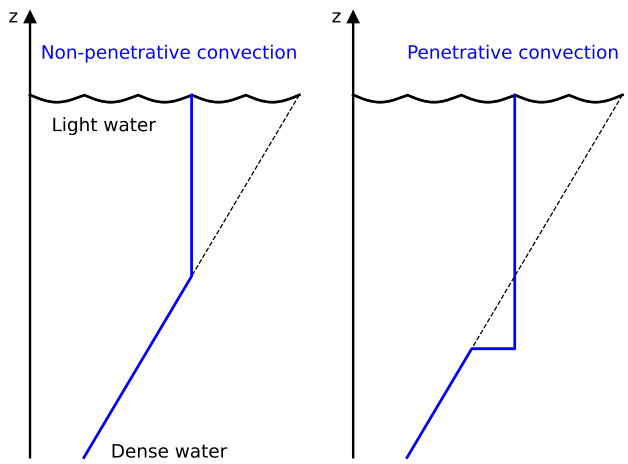

Figure 1 : Evolution of the temperature vertical profile for a non-penetrative and penetrative convective event starting from a stratified initial condition (dashed line).

When heat (or buoyancy) is removed at the surface of the ocean, a thin thermal layer of dense water forms, and, in localized places, convective thermals form and drain the upper layer by forcing cold dense water downward. As thermal plumes penetrate in the mixed layer, they entrain surrounding water but also retain part of their coherent structure ; yet the structure of the large convective cells in the fully turbulent regimes is still poorly known (Chillà et al. 2012). Whether or not the thermals impact the base of the oceanic mixed layer as coherent structures is key to describe the entrainment process which erodes the underlying stratified ocean. If the thermal has lost all its kinetic energy as it reaches the bottom of the mixed layer, it will erode it by a peeling process also known as "non-penetrative convection". By contrast if the thermal keeps a non negligible vertical velocity as it reaches the base of the mixed layer, it will overshoot it and more efficiently entrain water from below. This is "penetrative convection" – see Fig. 1.

These coherent plumes cannot be represented in ocean models and need to be parameterized to get an accurate representation of the mixed layer. While it is easy to capture non-penetrative convection with simple parameterizations, penetrative convection remains a challenging process to model because of the additional unknown (density jump below the mixed layer ; see Fig. 1right). For penetrative convection, Giordani et al. 2020 recently implemented a mass flux parameterization scheme which is inspired from the work done in the atmospheric community for convective events (see also Canuto et al. 2007). The mass flux model consists in considering convective structures as plumes of cold water falling as coherent structures from the surface into the mixed layer. In practice, the mass flux scheme has many adjustable parameters, and historically, these parameters have been tuned to match observations of atmospheric convection.

Objectives

We will conduct systematic experiments of convection on the Coriolis platform, and complement this dataset with Direct Numerical Simulation. This dataset will then be used to assess and calibrate parameterizations of convection.

Methodology

Experiments on the Coriolis platform

The Coriolis platform, the largest rotating tank in the world (13 m diameter), provides unique opportunities for repeated, well calibrated fluid dynamics experiments. The tank will be heated from below by a grillwork of electrical wires embedded in a shallow water layer (5 cm thick) separated from the main working volume by an aluminum sheet (upside down configuration with respect to the ocean ; see the successful experiment of Read et al. 2015). After the set-up installation, **we will perform 4 reference experiments**. (i) First we will do a plain Rayleigh-Bénard experiment without rotation and without stratification. To our knowledge this will be the first Rayleigh-Bénard experiment at high Rayleigh number with such a large aspect ratio. (ii) In the second experiment, we will set the initial profile with the linear stratification, to observe the progression of the mixed layer produced by convection. (iii) The third experiment will consist in repeating these experiments with rotation. The maximum Coriolis parameter f corresponds to a period of 60 s, for which the Rossby number $Ro = 0.05$: well in the oceanic regime. (iv) Finally the effect of surface shear will be reproduced by a sudden change of the tank rotation period (see Sous et al. 2013). A comprehensive set of instrumentation will be deployed for all these experiments. The temperature will be measured at several points in the bottom plate to evaluate the Rayleigh number. Vertical profiles of temperature and salinity will be obtained by **two traveling probes**. Time records will be also obtained at fixed height. The main flow characterization will be made by a **horizontal laser sheet** covering the whole tank, with **vertical scan to get volume cartography** ; a technique already tested by Negretti et al. 2021. Top view imaging will be done by **two high resolution cameras, capturing horizontal velocity fields by Particle Imaging Velocimetry, and temperature fields by laser Induced Fluorescence**, a technique developed by Caudwell et al. 2016. **A second laser system will be used to get vertical sections of velocity and temperature**.

Direct numerical experiments with the basilisk model

We will use the state of the art Basilisk model (`http://basilisk.fr`) to build a high resolution numerical clone of the platform. The first task will be to calibrate the model in order to reproduce the dynamics observed on the platform. We plan to use a high order upwind advection scheme that handles dissipation implicitly. The grid resolution will be 1 mm (adjusted with **Adaptive Mesh Refinement**) as a trade-off between accuracy, and ability to perform multiple experiments. After this calibration phase, we will launch **100 simulations to pave the parameter space**. For each simulation, we will compute the average evolution of the mixed layer and covariances of the fluctuating quantities. All variables and simple diagnostics will be included in the database. Based on our prototype low-resolution simulation, we estimate that we will need O(20 Mh) of CPU time. These runs tested on a local cluster and then will be carried on the **national High Performance Computers (HPC)** for which we have a long experience of scientific computing.

Calibration of the mass-flux parameterization for oceanic convection

In the mass flux parameterization of Giordani et al. 2020, the continuous formulation (including the adjustable parameters) and underlying hypothesis of the scheme was directly taken from the atmospheric community. To **adapt this parameterization to the ocean**, we need to measure the dynamical characteristics of the plumes (the fractional area occupied by the plumes, the vertical velocity of each individual plume, the buoyancy profile in the plumes, where all three quantities are function of the vertical coordinate. We also need the entrainment and detrainment coefficients (how the plume mixes with the environment), the drag coefficient (which capture the slowdown of the plume due to pressure perturbations), along with other key parameters. In order to calibrate these parameters, we will **identify the coherent structures with tracer methods** (Honnert et al. 2016) and **compute composites of theses plumes**. With such composites, we will compute the covariances of the turbulent quantities in the frame of reference of the plume and calibrate all parameters of the plume model. We will adopt a **Bayesian perspective** and model those parameters as random variables : the objective is to draw samples from the posterior distribution which describes the probabilistic knowledge that we have on the parameters after observing the data. For the validation, we will run 1D models with the parameterization and compare it to the experiments with macroscopic metric such as the depth of the mixed layer and the mean turbulent kinetic energy.

Mentoring plan

This thesis will be co-supervised by B. Deremble at IGE, and J. Sommeria at LEGI. The technical support will be provided by the research engineers at LEGI and IGE. The thesis will be organized in several steps delimited as follows.

- Months 1-3 : The first year of the thesis will be entirely devoted to the realization of the experiments on the Coriolis platform. During the first three months, the PhD student will build the experimental setup with the help of the research engineers working on the Coriolis platform. The main task will be to set up the heating cables covered by aluminum plates, as well as all the observation methods of the experiment. At the same time, he or she will familiarize himself or herself with the bibliography of oceanic convection and lead reading groups on the subject.

- Months 4-12 : Then will come the realization of the first experiments with phases of tests and an adjustment of the measuring devices (camera, lasers, probes). Finally, he or she will carry out the convection experiments described in the project (forced convection in a rotating reference frame). In parallel to this first phase of the thesis B. Deremble will carry out numerical simulations to complete the data observed on the platform. All these data will be aggregated in a database.
- Months 13-18 : Organization of the results and publication of the first paper to describe the dynamics of forced convection in a wide range of parameters.
- Mois 19-30 : The second part of the thesis will be dedicated to the fine analysis of the experimental and numerical data. In this phase, the PhD student will set up a calibration method for oceanic parameterizations. This phase also opens the possibility of an analytical development to include the effect of rotation in the parameterization and calibration of rotation-specific parameters.
- Mois 31-36 : The last months of the thesis will be dedicated to the writing of scientific papers and the writing of the thesis.

Objectives of valorization of the doctoral student's research work : dissemination, publication and confidentiality, intellectual property rights,...

No confidentiality clause, the main objective is to publish in A-ranked journals, and to give papers in international conferences (EGU, Ocean Sciences Meeting, etc) and targeted workshops.

Collaborations

This project will be conducted in close collaboration with M.E. Negretti (LEGI), an expert in mixing processes, and F. Lemarié (INRIA Grenoble), an expert in ocean modeling and mixing layer parameterization.

Positioning of the thesis

This thesis project is part of a more global strategy of the MEOM (IGE) and MEIGE (LEGI) teams to position themselves on the study of oceanic processes in the vicinity of the air-sea interface, coupling and its implications for different aspects of the climate system.

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