Proposed PhD Research Project:

Developing quasigeostrophic ocean circulation model for irregular domains

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Project Description

This Project is for a student who is interested to develop skills in computational modelling for geophysical fluid dynamics, numerical algorithms for solving PDEs, coding and scientific computing. The present state-of-art of the ocean general circulation modelling involves an hierarchy of models. On the top level there are climate-type global Earth system models that have heavily parameterized, and, therefore, very badly represented, primitive-equations oceans, because of the necessity to balance all the global complexity involved. On the next level there are so-called "eddy-resolving" ocean models, which are very expensive, both computationally and in terms of the involved output data analyses. The above types of models need specialized research institutions and long-term investments to deal with them. On the next level there are so-called "intermediate-complexity" models, such as multi-layer shallow-water dynamics in simple configurations and its asymptotic quasigeostrophic (QG) incarnation. There are thousands of papers published with the QG approach, proving that it is one of the great theoretical successes, aiming at reproducing realistically physical processes, without capturing many details.

The main problem with QG models is that they are configured to work only in simple rectangular domains, such as double-periodic or closed rectangles, or straight channels, because of the involved direct elliptic-problem solvers that use Fourier transforms. Here, use of indirect (iterative) elliptic solvers, more adaptable for general domains, is ruled out, because they require too many iterations to converge to an acceptable level of numerical accuracy. Why is this a big deal? Take a look at Fig. 1, which illustrates the point: the left panel shows realistic ocean basin, with specific shape of the coastline, and the right panel shows QG model simulation in the square domain representing idealized North Atlantic basin. Can we do realistic coastline for QG-type conceptual and process studies? Can we develop QG model of the Mediterranean Sea, with all its complicated coastline? The answer is YES.

The main objective of the Project is to transform the QG modelling landscape and push it to the next level of physical complexity. More specifically, the idea is to upgrade and test in various settings the existing and well-respected QG (oceanic and atmospheric) model code "PEQUOD" (in Fortran). This particular numerical model is algorithmically the most efficient one out of the existing QG models and is widely used (in simple domains); e.g., see Shevchenko and Berloff (2015) to get an idea about highly turbulent flow regimes. The starting development will be by considering individual rectangular capes and bays, then, we'll move to some realistic coastlines, as in Fig. 1.

Work Plan

(1) The first stage of development is to upgrade the direct elliptic Helmholtz-type solver used for inverting potential vorticity fields into the corresponding velocity streamfunctions. The proposed capacitance matrix method is known and has been implemented in the past (Blayo and Provost 1993), hence the main effort will be on reviving this technology, then, implementing and testing it. Similar effort was made recently by Zhong et al. (2016) team, but their codes are not public.

(2) Re-coding boundary conditions for the CABARET advection operator (Karabasov et al. 2009) which is part of the QG model dynamical core. For this development the student will be encouraged to interact with Prof. Sergey Karabasov from the Queen Mary University of London.

(3) Testing the code in some specified and interesting configurations. This can be the North Atlantic with and without the Gulf of Mexico, or the South China Sea with the Luzon strait, or the Mediterranean Sea, but there are other choices to discuss.

(4) Developing postprocessing software codes that take into account irregular boundaries.

(5) Optimization of the code for parallel multi-core computing.

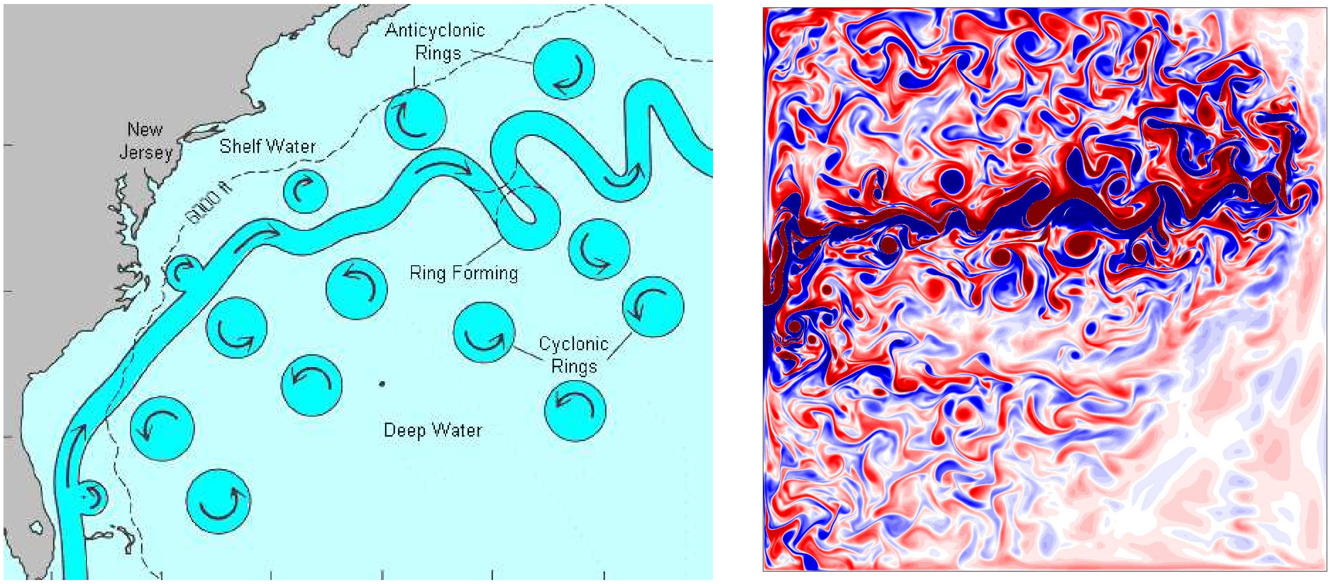

Figure 1: Illustration of the Gulfstream current in the North Atlantic (left panel) and idealized square-domain QG model solution (right panel). The left shows the realistic US east coast line, with the Gulfstream jet separating near cape Hatteras and surrounded by intense vortex-type rings and (not shown) multi-scale weaker eddies; the separated jet continues to the east, meanders, sheds rings, generates its own large-scale low-frequency variability, controls global transport of various properties and impacts on the atmosphere and global climate. The shape of the coastline matters, but (right panel) idealized QG models are not yet capable of handling this, despite the fact that they capture qualitatively and quantitatively realistic Gulfstream jet, with meandering, ambient vortices and multi-scale eddies; shown is an instantaneous snapshot of the upper-ocean potential vorticity anomaly, which is fundamentally important descriptor of the corresponding general circulation. In summary, there are numerous examples of physical and numerical-modelling problems that involve complicated coastlines, and this point is illustrated here with the simple example.

Prerequisites: Interest in mathematical modelling and numerical methods, coding skills, some knowledge of PDEs, good taste for scientific computing; experience in computational fluid dynamics is desirable.

Broad Impacts: This Project would fit a student who wants to stay on track in software development, mathematical modelling, scientific computing, numerical methods, fluid mechanics, mathematical geophysics.

References

Blayo, E., and C. Provost, 1993: Performance of capacitance matrix method for solving Helmholtz-type equations in ocean modelling. *J. Comp. Phys.*, **104**, 347-360.

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