Workshop on submesoscale dynamics and biology on steep slopes

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Winter frontal variability at submesoscale in the Gulf of Lions as observed with gliders and simulated by a very-high resolution model

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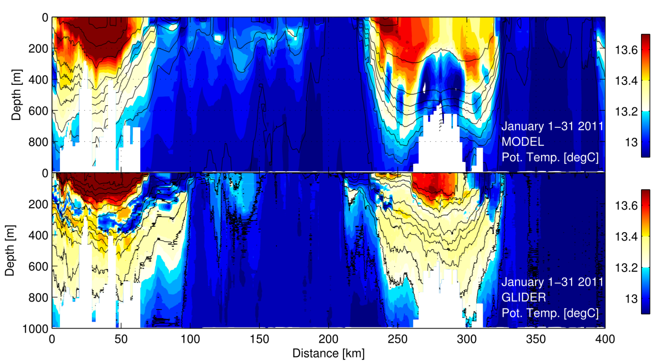
Since 2010, sustained observations of the circulation and water properties of the NW Mediterranean Sea have been carried out by gliders in the framework of the MOOSE observatory (Mediterranean Ocean Observatory System for the Environment: http://www.moose-network.fr/). They regularly sampled the wintertime Northern Current (NC), the deep convection zone as well as the North Balearic Front (NBF). These two baroclinic flows consist in density fronts especially steep during periods of deep convection when the offshore mixed layer reaches great depths.

In the gliders data, the NC front and the NBF both clearly exhibit evidences of vertical exchanges of tracers. In order to investigate the dynamical characteristics of these fronts, we estimate the Ertel Potential Vorticity (EPV) based on the glider data. It reveals remarkable layers of negative EPV that can extend down to about 100m depth within the stratified part of the NC front. Under such extreme conditions, symmetric instability might be able to grow and results in overturning circulations along isopycnals at a prescribed wave length in agreement with observations.

We also use a numerical model (SYMPHONIE) to further assess the ability of gliders to accurately estimate the EPV at the front, and pointing out the driving mechanisms being able to destroy the potential vorticity and trigger frontal instabilities. The model is run in a regional configuration of the NW Mediterranean Sea at 1km horizontal resolution and force with realistic forcing for the Winter 2011. The model turns out to be able to well represent the open-ocean deep convection, as well as frontal submesoscale circulation features.

In the model, we found that during episodes of strong winds, EPV is significantly extracted at the NC front by the mechanical action of down-front winds. The western part of the Gulf of Lions is especially subjected to this phenomena due to the orientation of the NC there. Negative potential vorticity is found in the area of down-front winds down to about 100m depth for periods of a few days. This looks very similar to the glider observations and explain the initiation of vertical exchanges of oceanic tracers at the front that are observed. These vertical circulations might be important for the heat and salt exchanges between the NC and the NBF and the center of the basin, and in particular the deep convection area.



(lower panel) Glider measurements of potential temperature during an open-ocean deep convection event in the Gulf of Lions in January 2011. Black contours represent isopycnals. The NC front is identifiable by the outcropping isopycnals. (upper panel) Similar figure from a realistic simulation performed by the SYMPHONIE model.

Mesoscale eddies in the Arabian and Oman Seas and their impact on the PGW outflow

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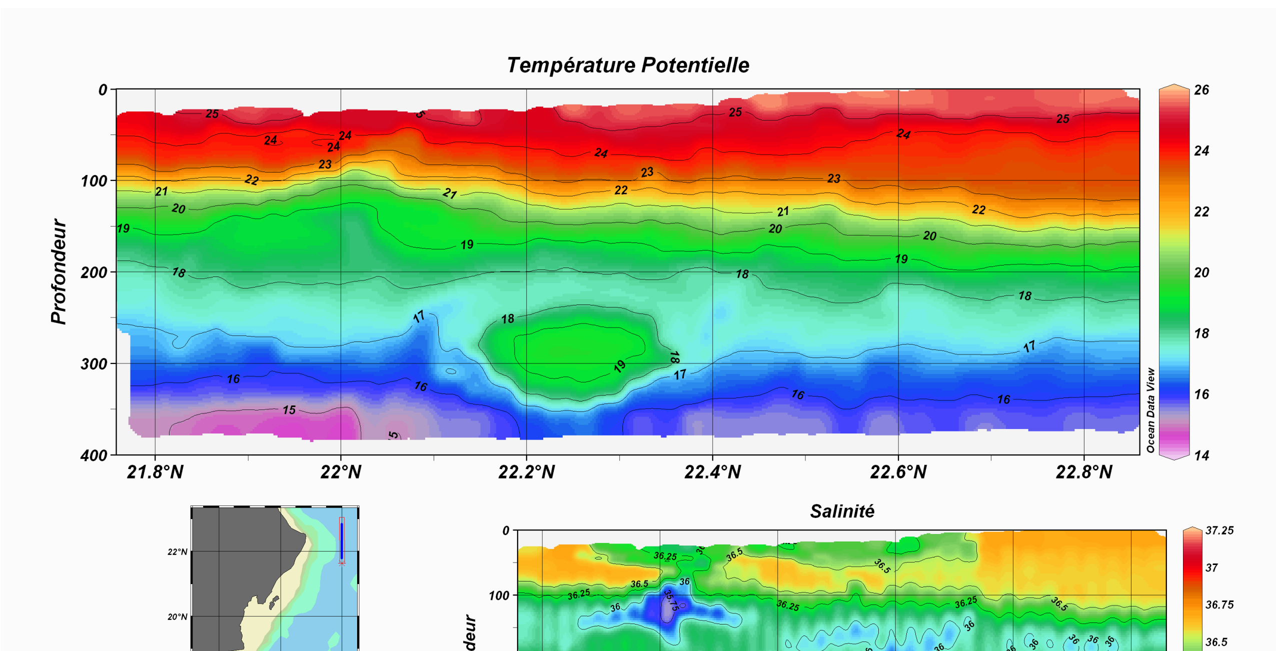
Using altimetric and ARGO data, and the output of high-resolution HYCOM model simulations, we characterize the structure, cyclicity and origin of the mesoscale structures in the Sea of Oman and in the Arabian Sea. Coastal currents are established in summer and winter under the strong monsoon wind forcing. In spring and autumn, when the winds relax, these currents destabilize and produce rows of mesoscale eddies, with about 60-80 cm/s velocity, 50-100 km radius, alternate polarities and a deep dynamical influence (often reaching 1000m depth). These eddies appear with similar characteristics and at close locations, for every season, over a 20 year period. Once formed, they can be reinforced by the direct action of the wind stress curl at the surface, followed by a vertical transfer of momentum, or by the merger with eddies generated by the destabilisation of Rossby waves. Finally, these mesoscale eddies strongly perturb and advect offshore the Persian Gulf Water (PGW) outflow. Several ejection processes have been identified: the recirculation near the Strait of Hormuz, the ejection as filaments and small eddies near Ra's al Hamra, the trapping in a lee eddy downstream of this cape, and the detachment of this eddy. or the ejection in filaments or eddies via the Ra's al Hadd jet. These processes induce, via mixing, a deepening and a widening of the outflow, and a noticeable decrease in its thermohaline anomalies.



Salinity cross section south of Ra's al Hadd during Physindien 2011, showing a submesoscale lens eddy of PGW

Plankton dynamics at the mesoscale, a case study of a coastal cyclonic eddy in the Southern California Bight

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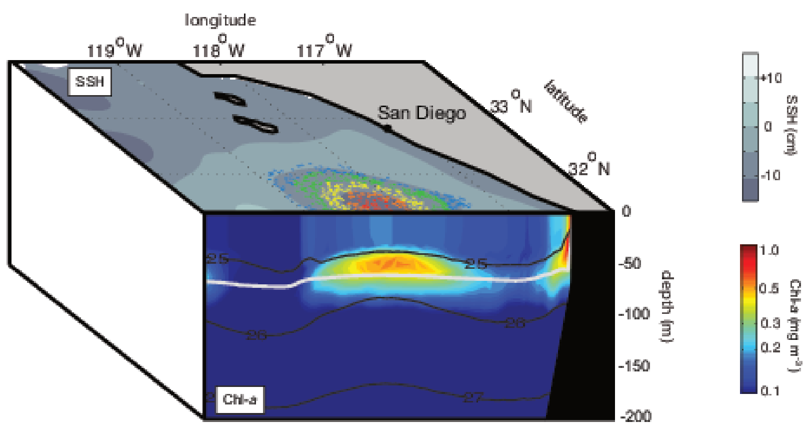
Eastern boundary upwelling systems (EBUS) are characterized by high biological production along the coast, contrasting with oligotrophic waters offshore. This cross-shore gradient is affected by intense mesoscale eddy activity. Eddies that are formed at the coast move offshore, entraining and redistributing nearshore nutrients and planktonic organisms. High planktonic biomass can be found in these eddies months after detaching from the coast. The mechanisms driving these patterns and their ecological impacts in EBUSs are still in debate. We focus our analysis on the Southern California Bight (SCB), part of the Californian EBUS. To characterize and understand the influence of mesoscale eddies on planktonic ecosystems in the SBC, we use a numerical approach coupling the Regional Ocean Modeling system (ROMS), at 5 km horizontal resolution, with a multiple size class planktonic ecosystem model (NEMURO). Combining Eulerian and Lagrangian analyses, we were able to follow one specific cyclonic eddy formed in the Southern California Bight as it detached from the coast and migrated offshore. Within this tracked eddy, we characterized the ecosystem dynamics in time and space and aimed to elucidate the mechanisms that influence the planktonic ecosystems trapped in eddies, and the relative contribution of horizontal and vertical advection in determining local production.



Snapshot of the Sea Surface Height (SSH) (in grey scale, top figure) and of the chlorophyll-a (bottom figure) across a cyclonic eddy in the Southern California Bight. This particular cyclonic eddy, formed at the coast, is characterized through the SSH field and presented enhanced subsurface chlorophyll-a compared to the outside of the eddy. This eddy has been tracked using Lagrangian particles (colored dots on the top figure), backward and forward in time. The color code refers to different pools that were defined based on their position in the eddy at the time of this snapshot, from the center (red and orange) to the edge (green and blue). Superimposed on the chlorophyll-a concentration are isolines of density (black) and the euphotic depth (grey dashed line).

Frontal, wake eddy, topography control and ecological constraints of fish spawning habitat

Laurent Chérubin

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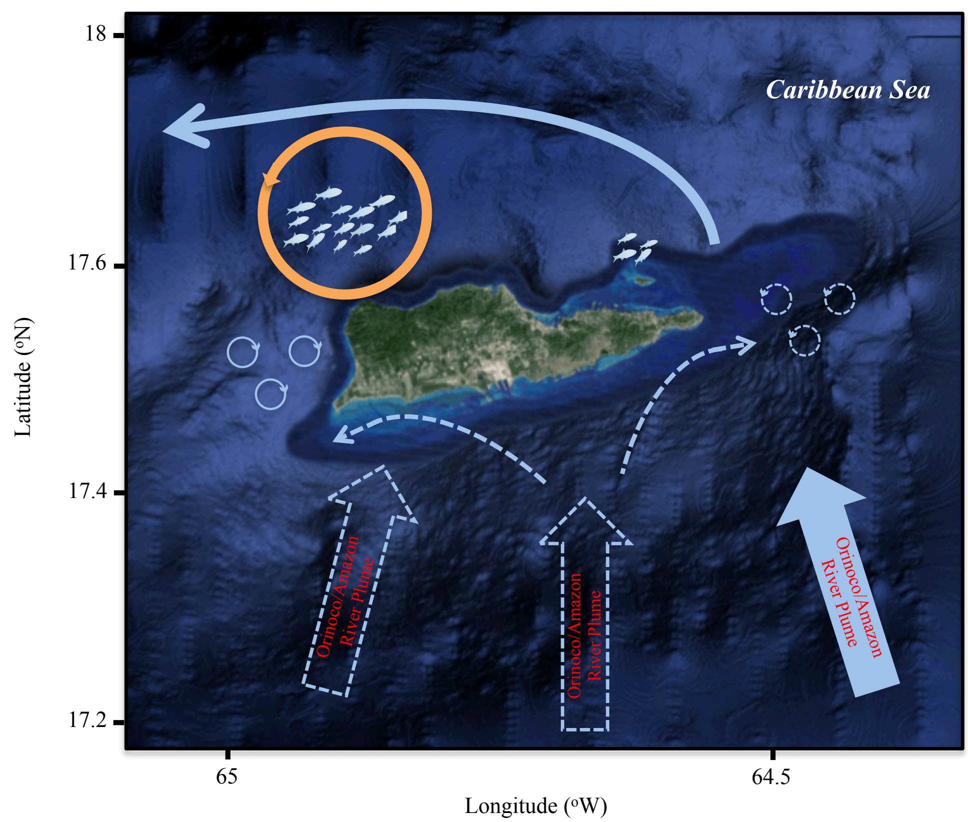
Fish have to fulfill various needs including that of surviving from egg to juvenile stage and dispersing across different habitats while minimizing predation and maximizing food intake. The spawning location of marine fish typically has been viewed as an adaptive choice to increase opportunity for larval feeding, reduce larval, egg and adult predation, or stabilize transport toward suitable nursery locations. The access to frontal or wake eddy is one of the processes that allow fish larvae to disperse in a food rich environment with limited predators and which provides a return or transport mechanism to their nursery ground. The return mechanism is particularly critical in the context of isolated island as it is most likely the only and closest to nursery habitat available. Therefore the characteristics of such eddies, hence their formation mechanisms would ultimately influence the successful larval transport success. Here we present the role of topography on the eddy vorticity generation and its role on the larval retention process in two types of environment, which illustrates a diverging evolutionary adaption toward a similar ecological goal.



Amazon and Orinoco plume driven island wake eddies and larval recruitment gradient on the the reefs of St. Croix, US Virgin Island

Various regimes of instability and formation of coastal eddies along the shelf bathymetry

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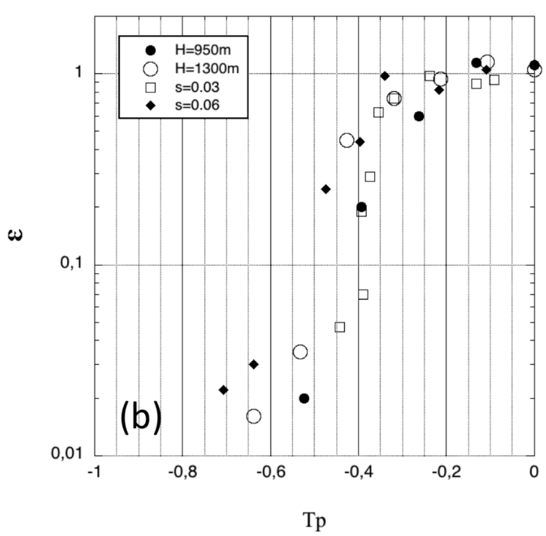
This numerical study aims at understanding the impact of the bottom topography on the stability of a geostrophic surface coastal current and the formation of coastal meanders and eddies.
A continuously stratified model is used, extending the analysis presented in Poulin et al., 2014 for a two-layer stratification. Simulations are performed using the Regional Ocean Modeling System (ROMS). We use an idealized periodic channel configuration with a geostrophic coastal current jet (modeled with a linear-gaussian profile) flowing along an hyperbolic tangent shelf bathymetry. The impact of the shelf bathymetry on the current stability is assessed by varying the shelf slope, the depth under the current jet and the vertical stratification (i.e. the first baroclinic deformation radius), while the geostrophic current remains unchanged.
Three distinct dynamical regimes are identified: a standard baroclinic instability, characterized by large mesoscale anticyclones that detach from the current; a trapped coastal instability, with small eddies propagating along the shelf and showing a marked baroclinic nature, i.e. anticyclonic (cyclonic) structures in the upper layer and cyclonic (anticyclonic) structures in the lower layer; finally, a stronger topographic stabilization leads to a weakly unstable current with no eddies formation. Three governing parameters are used to distinguish the three regimes, namely: the topographic parameter ($\mathsf{T_p}$), a depths ratio (γ) and the Burger number (Bu). Besides, we show that the non-linear amplitude of the unstable perturbations is controlled by the shelf bathymetry. In the standard baroclinic regime, the unstable perturbations reach a finite amplitude leading to the formation of large meanders and mesoscale eddies. In the trapped coastal instability regime, both the meanders amplitude and the unstable wavelength are reduced. Once the first coastal eddies are formed along the shelf, a secondary process breaks them out and lead to sub-mesoscale perturbations. This direct cascade towards small scale induces a re-stabilization of the coastal current.



Dimensionless nonlinear saturation parameter ϵ as a function of the topographic parameter $\mathsf{T_p} = -V_{\mathrm{TRW}}/U$ where V_{TRW} characterizes the speed of topographic Rossby waves and U the jet speed.

From carbon export to the foraging of marine top predators: an end-to-end analysis of the (sub)mesoscale dynamics in the Kerguelen region

Francesco d'Ovidio

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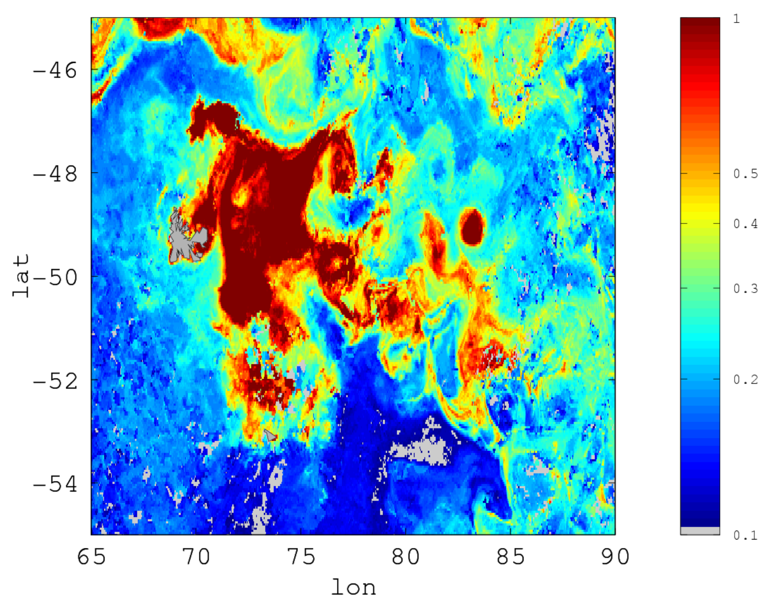
Large parts of the Southern Ocean waters are rich in macronutrients, but phytoplanktonic blooms occur in a patchy and localized way. This is in part due to presence of sources of limiting micronutrients scattered along the continental breaks, whose inputs are stirred into the open ocean very inhomogeneously. A dramatic example of this situation is provided by the region around Kerguelen archipelago (Indian sector of the Southern Ocean). Here, the high nutrient, low iron waters transported eastward by the Antarctic Circumpolar Current encounter the iron-rich Kerguelen shelf break. As a consequence, a plume of high chlorophyll water develops east of the plateau, extending from the shelf break for hundreds of kms into the open ocean, and contrasting with the low chlorophyll situation west of the plateau. The extension of Kerguelen bloom has been shown to be strongly modulated by the intense mesoscale activity present in this region and its primary production supports a complex trophic web which includes important stocks of krill, mesopelagic fishes (myctophyds) and large colonies of marine top predators (like sea birds and seals). By combining in campaign data, satellite observations, and biologging, here we will take an end-to-end approach and describe the mechanisms by which the ocean physics impacts the regional biogeochemistry firstly by redistributing iron-rich coastal waters into the open ocean, and then by focusing on the trophic interactions. We will consider in particular the role of mesoscale eddies and submesoscale fronts, whose temporal dynamics resonates with biological processes and organises the variability of marine eco-biogeochemistry from carbon export to the foraging of elephant seals.

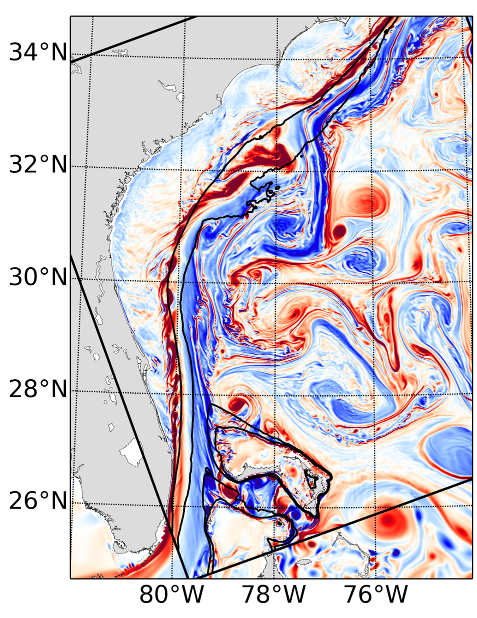


The bloom of chlorophyll (μg/l, December 2011) east of Kerguelen is fueled by the iron coming from the shelf break and redistributed eastward by the ocean upper circulation. The intense meso- and submesoscale activity strongly constrains the variability of the eco-biogeochemical processes in this region, from the carbon export to the patchiness of mesopelagic fishes, up to the foraging activity of marine top predators.

Instability and eddy formation in the Gulf Stream over the continental slope

Jonathan Gula
LPO, Université de Bretagne Occidentale, UMR6523, Brest, France

Meanders and eddies are routinely observed in the Gulf Stream along the southeastern U.S. seaboard. We analyze here the instability processes that lead to the formation of mesoscale and submesoscale eddies in the Gulf Stream over the slope and how the eddies impact the cross-shelf and vertical exchanges of momentum and tracers, using high resolution realistic simulations (dx=750m). Energy is transferred from the mean flow to the eddies following the Straits of Florida and past a topographic feature called the Charleston Bump, with regions of eddy-to-mean conversion in between. The eddy activity between the Straits and the Bump is mostly a barotropic mechanism driven by current-topography interactions. The positive relative vorticity on the cyclonic side of the Gulf Stream is strongly intensified in the Florida Straits due to topographic drag along the continental slope. Downstream from the Straits the current partially separates, becomes unstable to horizontal shear instability, rolls up and forms streets of submesoscale vortices. The baroclinic instability is stabilized by the slope everywhere except past the Bump, where the flow is deflected seaward. It is locally strongly unstable to mixed barotropic-baroclinic instability and forms large mesoscale frontal eddies. We also address the finite-amplitude behavior of a frontal eddy, including its structure, propagation, and emergent submesoscale interior and neighboring substructure using very high resolution realistic simulations (dx=150m). A rich submesoscale structure is revealed inside the frontal eddy with localized regions of intense upwelling bringing cold and fresh water from the upwelled cold of the eddy inside the surface mixed-layer. Finally, virtual Lagrangian particles are deployed in the model solutions to illustrate and quantify the impact of eddies in generating cross-shelf fluxes of tracers and in mixing tracer properties.



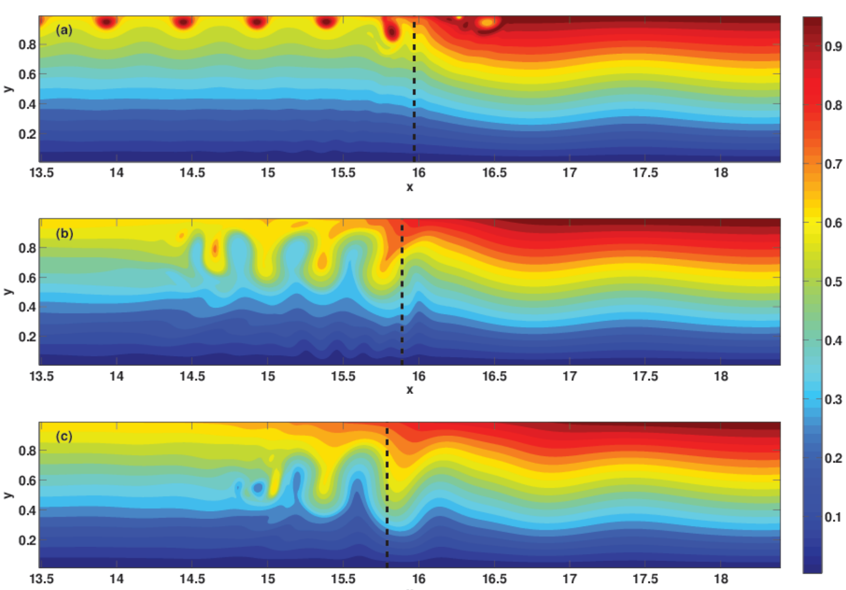
Meanders and eddies from topographic transformation of coastal-trapped waves

E. R. Johnson

Department of Mathematics, University College London, London, United Kingdom

This talk describes how topographic variations can transform a small-amplitude, linear, coastal-trapped wave (CTW) into a nonlinear wave or an eddy train. The dispersion relation for CTWs depends on the slope of the shelf. Provided the cross-shelf slope varies sufficiently slowly along the shelf, the local structure of the CTW adapts to the local geometry and the wave transformation can be analyzed by the WKBJ method. Two regions of parameter space are straightforward: adiabatic transmission (where, at the incident wave frequency, a long wave exists everywhere along the shelf) and short-wave reflection (where somewhere on the shelf no long wave exists at the incident frequency, but the stratification is sufficiently weak that a short reflected wave can coexist with the incident wave). This talk gives the solutions for these two cases but concentrates on a third parameter regime, which includes all sufficiently strongly stratified flows, where neither of these behaviours is possible and the WKBJ method fails irrespective of how slowly the topography changes. Fully nonlinear integrations of the equation for the advection of the bottom boundary potential vorticity show that the incident wave in this third parameter regime transforms into a nonlinear wave when topographic variations are gradual or into an eddy train when the changes are abrupt.

Rodney, J. T., & Johnson, E. R. (2014). Meanders and eddies from topographic transformation of coastal-trapped waves. Journal of Physical Oceanography, 44, 1133-1150. doi:10.1175/JPO-D-12-0224.1



The potential vorticity on the the slope. A small amplitude long shelf wave propagates from the right. The shelf slope decreases as the wave passes the dotted line. (a) A rapid slope decrease. The wave energy is transmitted as eddies. (c) A gentle slope decease. The wave energy is transmitted, at least initially, as long nonlinear waves (b) An intermediate transition. The wave energy is transmitted initially as long nonlinear waves which then break into eddies.

Anticyclone formation through submesoscale interactions at the shelf break

M. J. Molemaker
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The California Undercurrent (CUC) flows poleward mostly along the continental slope. It develops a narrow strip of large negative vertical vorticity through the turbulent boundary layer and bottom stress. In several downstream locations, the current separates, aided by topographic curvature and flow inertia, in particular near Point Sur Ridge south of Monterey Bay. When this happens the high-vorticity strip undergoes rapid instability that appears to be mesoscale in "eddy-resolving" simulations but is substantially submesoscale with a finer computational grid. The relative vorticity in the CUC is much less than $-f$ and Ertel potential vorticity is negative. This instigates ageostrophic centrifugal instability. The submesoscale turbulence is partly unbalanced and has a forward energy cascade, elevated local dissipation and mixing, dilution of the extreme vorticity values, and diapycnal velocities and mixing. Further downstream the submesoscale activity abates, and the remaining eddy motions exhibit an upscale organization into the mesoscale, resulting in long-lived coherent anticyclones in the depth range 100-500 m (previously called Cuddies) that move into the gyre interior.

Planktonic ecosystem response to meso- submesoscale dynamics above a shelf slope

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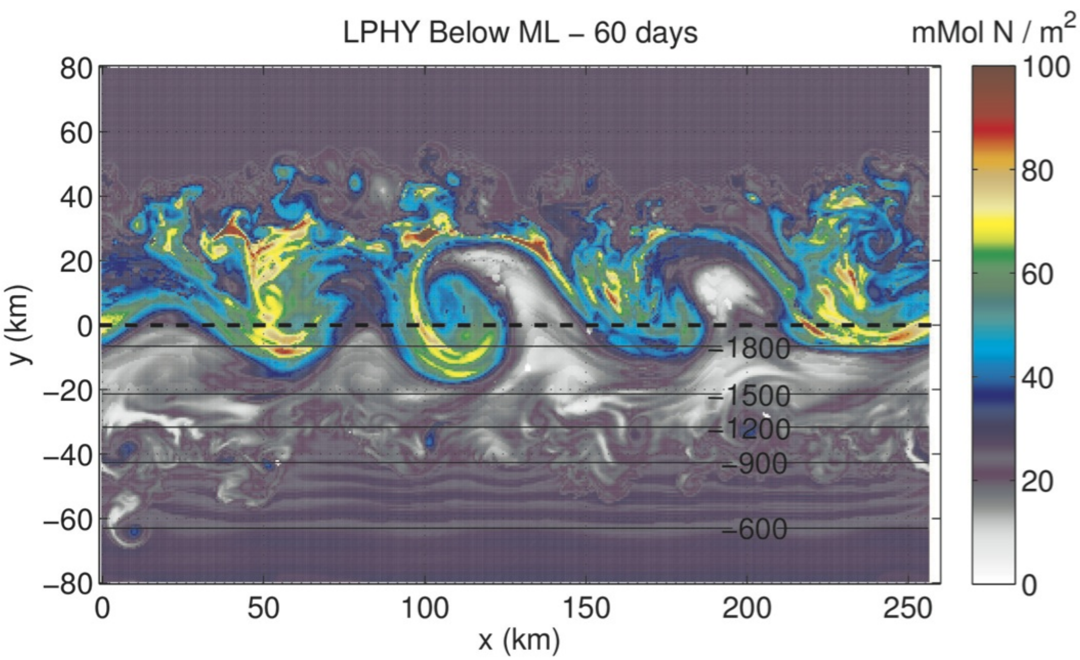
In this numerical process study, we examine the impact of the relative positions of a coastal current and the continental slope on the dynamics of a planktonic ecosystem.

In the open ocean, previous studies have evidenced the importance of mesoscale and submesoscale turbulence on the structure and functioning of planktonic ecosystem (Rivière et Pondaven, 2006; Perruche et al, 2011). In coastal areas, the presence of the continental slope induces a complex ocean dynamics and impacts the spreading of biochemical tracers between the shallow continental shelf and the deep open ocean. The topographic parameter (ratio between the shelf slope and the isopycnal slope), the vertical aspect ratio (ratio between the depth of the current and the total depth) and the Burger number control the stability of surface coastal currents and the emergence of meso and submesoscale structures (Pennel et al, 2012; Poulin et al, 2014). Thus, different positions of the current above the shelf slope, by changing the local depth or the local slope, induce different dynamical regimes that may imply a large impact on ecosystems through changes in nutrient inputs from the deep ocean into the euphotic layer or changes in the cross-shelf transport.

Simulations of a geostrophically balanced gravity current with a mixed layer are carried out using the Regional Ocean Modeling System (ROMS). The domain consists of a re-entrant channel with an hyperbolic tangent shelf bathymetry. The 600 m horizontal resolution (12 grid points per radius of deformation) and the 60 vertical levels allow the model to resolve both the meso and submesoscale dynamics. An idealized biological model is included and accounts for the existence of two different trophic chains involving small and large species.

A suite of few months long simulations is performed with different positions of the coastal current above the bottom topography. The results are discussed in terms of primary production, cross-shore export of biomass and structure of the ecosystem.



Large phytoplankton concentration in subsurface bellow the mixed layer after a simulation of 60 days. Topography is indicated by isolines and the mid initial jet by a black dashed line.

Coastal mesoscale processes and submesoscale horizontal diffusivity during LATEX

A. Petrenko(1), A.M. Doglioli(1), M. Kersale(1,2), F. Nencioli(1,3), F. d'Ovidio(4), F. Diaz(1) and the LATEX group

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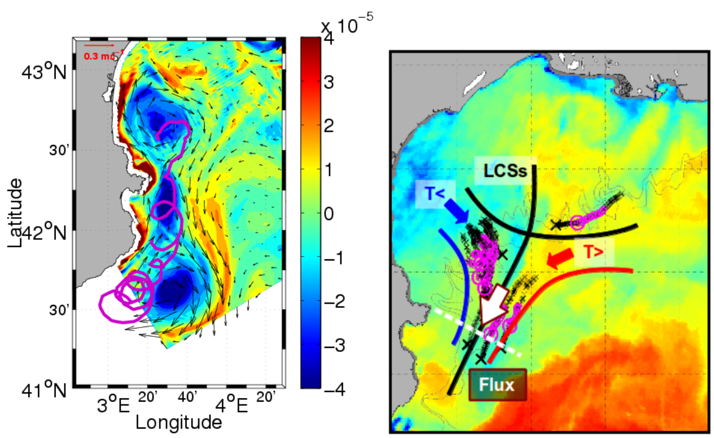
The LATEX project aimed to study the influence of coupled physics and biogeochemistry dynamics at the (sub)mesoscale on matter transfers within or between the coastal zone and the open ocean. LATEX was based on an integrated use of numerical modelling, remote sensing observations and *in situ* measurements, which combined classical oceanographic tools with Eulerian and Lagrangian sensors, gliders and a tracer experiment. A realistic 3D numerical model (Symphonie) was run from 2001 to 2011 at low resolution (3 km) in the Northwestern Mediterranean, with a nesting at high resolution (1 km) over the Gulf of Lion (GoL) (Hu et al., 2009). The project also included 4 cruises : from a pilot one in 2007 to a near month-long one with 2 RVs (Sept 2010), for which we developped a Lagrangian navigation sampling strategy (and accompagnying software ; Doglioli et al., 2013). During stratified summer conditions, generally following northwestern wind events, elliptical, shallow, anticyclonic eddies are observed north of Cape Creus (Hu et al., 2011a). Two different generation processes can create these mesoscale features (Hu et al., 2011b ; Kersalé et al., 2013). During the LATEX 2010 cruise, Lagrangian Coherent Structures derived from *in situ* data were associated with a front along which coastal waters escaped from the GoL (Nencioli et al., 2011). Transport fluxes are assessed (Nencioli et al., in prep.), as well as horizontal diffusivities, which are estimated using two approaches: i) by combining stirring rates estimated from Lagrangian drifters with cross-front surface temperature gradients (Nencioli et al., 2013); ii) by mapping a passive tracer's dispersion (Kersale et al., 2015). These mesocale processes (eddies, fronts...) have an influence both locally and on interregional exchanges, and impact biogeochemical and biological systems, as shown numerically with coupled physical-biogeochemistry modelling (Campbell at al., 2013), or with *in situ* data (Diaz et al., in prep).



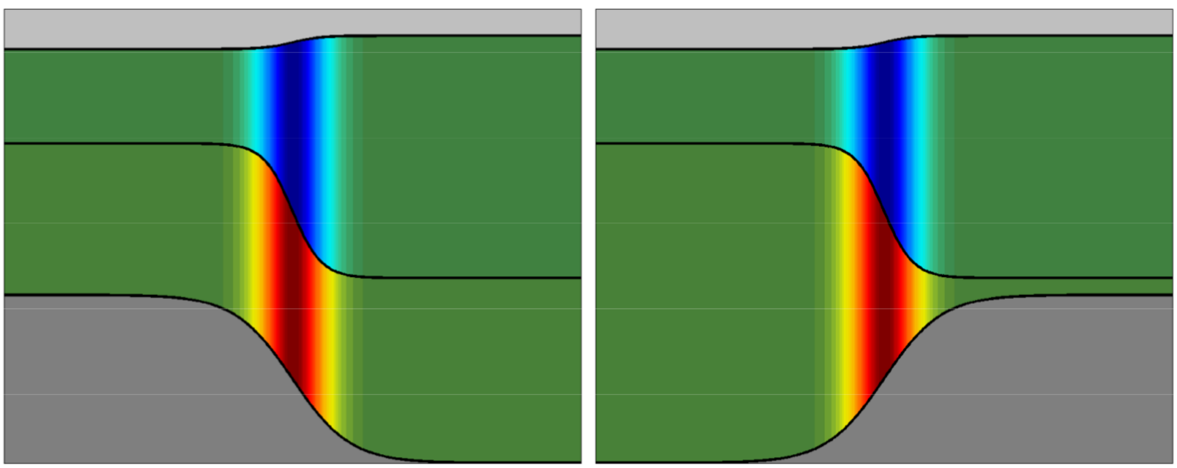
a) Modeled relative vorticity (s-1) and current velocity field at 20 m on Sept 3, 2009, and trajectory of a 15-m anchored Lagrangian drifter (08/26 to 09/12); from north to south note the following structures: Latex eddy, transient structure, Catalan eddy; derived from Kersalé, M., Petrenko, A. A. , Doglioli, A.M., Dekeyser, I., Nencioli, F. (2013), Physical characteristics and dynamics of the coastal Latex09 Eddy derived from in situ data and numerical modeling. J. Geophys. Res., Vol.118, pp.1-11, doi:10.1029/2012JC008229. b) LCSs and Lagrangian drifter trajectories on pseudo-SST image (Sept 15, 2010); derived from Nencioli, F., d'Ovidio, F., Doglioli, A.M., Petrenko, A.A. (2013), In-situ estimate of submesoscale horizontal eddy diffusivity across an ocean front. J. Geophys. Res., 118, doi:10.1002/2013JC009252.

The Stability Characteristics of Two-Layer Flow over a Steep Shelf

Francis Poulin

Department of Applied Mathematics, University of Waterloo, Canada

Sufficiently strong shear in the world's oceans become unstable and subsequently give rise to vortical motions that can be either barotropic, baroclinic or more generally a combination of the two. Instead of studying shear instabilities in three-dimensional geometries, it is much easier to consider these mechanisms in the context of multi-layer flows. One model that can capture many essential features of shear instability is a two-layer Shallow Water (2LSW) model. Furthermore, it is able to capture a wider range of phenomena than Quasi-Geostrophy.! ! In this talk, we investigate the instability of a geostrophic Bickley jet in the context of the 2LSW model. First, using linear theory in the context of a flat bottom we point out the different types of modal instabilities that are possible. This includes tracking how these modes change with stratification. Second, we then study the dynamics of the jet over a smooth shelf to determine what affect topography has on the different unstable modes. Most of our analysis will use linear stability theory but the results of some nonlinear simulations will also be presented.



Two examples of baroclinic shear flows in the context of a two-layer shallow water model. The flow on the left (right) is for prograde (retrograde) flow because the topographic Rossby waves propagate in the same direction as the current in the lower layer.

Eddy-driven ventilation of the Arabian Sea

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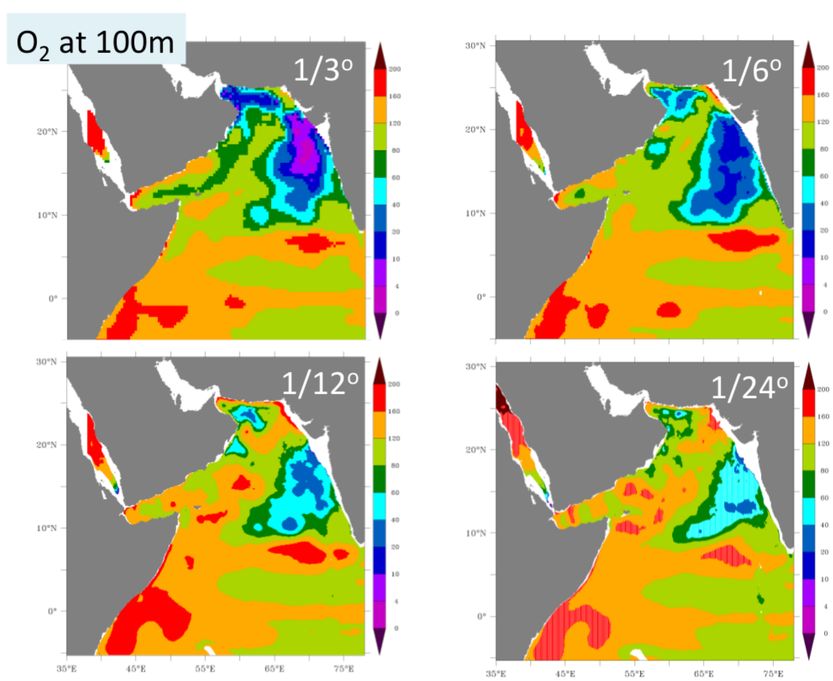
Center for Prototype Climate Modeling New York University, Abu Dhabi

The Arabian Sea (AS) is the site of the thickest, most persistent Oxygen Minimum Zone (OMZ), and its dynamics result from a complex interplay of biology and physics, providing a stark challenge to ocean general circulation models. In a suite of recent simulations of the AS using ROMS coupled to a biogeochemistry model, with 1/12° 1/24° realistic forcing, boundary conditions and horizontal resolutions ranging from 1/3° to 1/24°, it was found that Primary Production (PP) increased with increasing spatial resolution. This might seem unsurprising — increased eddy resolution is thought to increase transport of nutrients into the euphotic zone. However, these simulations also revealed increased oxygen at depth with increasing resolution (see figure, showing oxygen at 100m depth). This is unexpected because increased PP means increased nutrient-rich detritus falls into the dark ocean, driving bacterial respiration, which consumes oxygen — more productivity should mean less oxygen at depth.

Oxygen loss by respiration is typically balanced by ventilation: oxygen diffuses into the surface mixed layer and is equilibrated with the atmosphere on fast time scales (about a day), and this oxygen-rich water is mixed downward at a timescale determined by isopycnal mixing (on order months). Thus ventilated density layers, such as most of those in the North Atlantic, can maintain an annual cycle of depletion by bloom-driven respiration and restoration by ventilation.

The Arabian Sea, however, is geographically capped at 25° N by the Eurasian continent, preventing the mean ventilation of most of its deeper layers. Thus ventilation in the AS relies primarily on eddy-driven vertical transport. But increased vertical eddy transport should increase both productivity and ventilation. Why don't these processes compensate in their impact on oxygen at depth? A simple model for the interplay of the relevant processes will be proposed and discussed during the presentation.



A highly turbulent interocean exchange South of Africa

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(1) École Normale Supérieure, Département de Géosciences, Laboratoire de Météorologie Dynamique (LMD), IPSL, Paris , France
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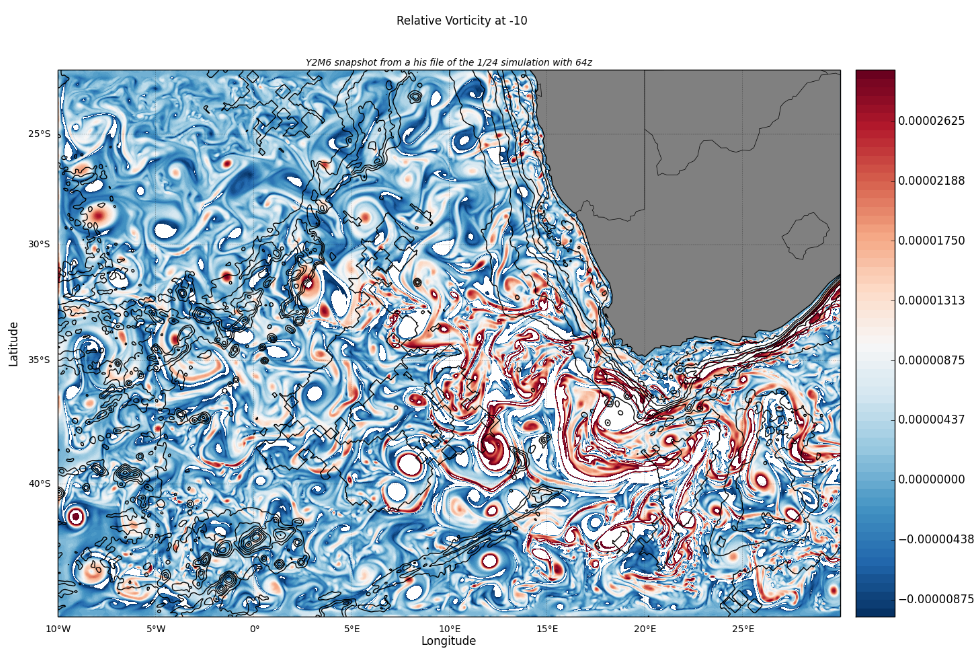
An accurate description of heat and freshwater fluxes across and between the atmosphere and the ocean is essential for understanding the current climate and its evolution. For this reason, ocean interbasin exchanges must be described and assessed thoroughly since they participate heavily in the heat and salt budget of each basin and, in combination with surface winds, they drive the Meridional Overturning Circulation (MOC), a three-dimensional circulation pattern that links the main ocean basins and spans their full depth.
South of Africa, these exchanges are complex and rely on large-scale density gradients, on the large-scale atmospheric circulation, local air-sea exchanges and on submesoscale and mesoscale processes. This region is a hot spot of oceanic turbulence where waters inflowing from the Indian, Atlantic and Southern oceans undergo to strong interactions and transformations before being redistributed, in particular, to the North Atlantic as part of the upper-branch of the MOC.
We will discuss recent results issued from modelling, fieldwork and satellite observations that converge with a new vision of the Indo-Atlantic connection.



Snapshot of surface relative vorticity from a ROMS regional configuration at 1/24° showing the complex ocean dynamics south of Africa

Downfront Winds in a Coastal Environment

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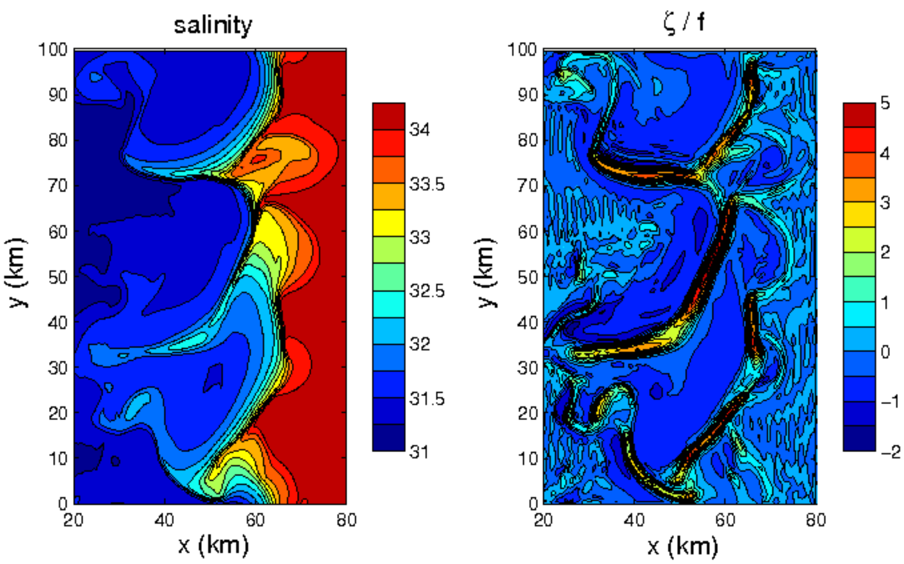
The influences of a downfront wind over a coastal front are studied numerically and contrasted with downfront winds over open ocean fronts. The presence of a coast results in a large cross-front pressure gradient, which in turn drives stronger frontogenesis, more extreme vorticity and straining fields, and stronger vertical velocities than are found in the open ocean. For two-dimensional flows symmetric instability dominates while for three-dimensional flows baroclinic instability dominates, although there are isolated regions of symmetric instability as well. Aspects of the Eulerian and Lagrangian mean flows, water mass transformation, and momentum budgets will be discussed and contrasted between coastal and open ocean environments in both two and three dimensions.



Sea surface salinity (left) and relative vorticity divided by the Coriolis parameter (right) on day 30 from a numerical model for a case of downfront winds over a sloping shelf. Eddies and meanders drive cross-shelf salt flux. Competition between baroclinic instability and Ekman transport results in strong, narrow fronts with large relative vorticity and intense vertical motions.

Meso and sub meso scale dynamics of coastal current along a steep shelf bathymetry

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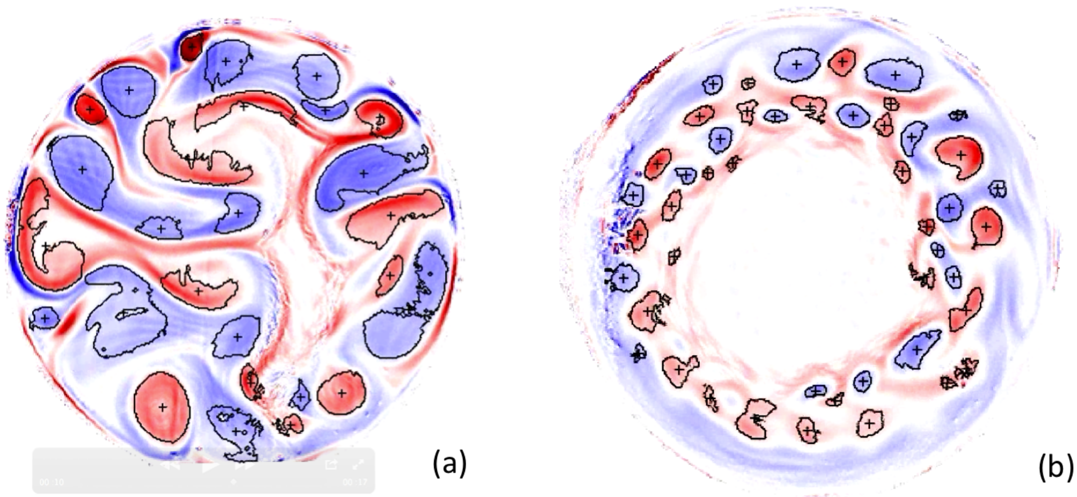
The impact of shelf slope on the stability of coastal currents and the nonlinear formation of coastal meanders and eddies are investigated by linear analysis, numerical simulations and laboratory experiments. The simulations were performed using an idealized configuration of the NEMO model and the laboratory experiments were achieved on the UME-LMD rotating platform. High resolution is achieved in both investigations (PIV measurements and numerical grid) in order to quantify accurately the meso and the sub meso scale structures. Our results confirm, for an idealized two-layer stratification, that the topographic parameter To (ratio between the shelf slope and the isopycnal slope of the current) is the relevant parameter to quantify the shelf impact on the linear and nonlinear dynamics of the surface current.
For a geostrophic coastal current, two different regimes of instability with distinct wavelength selection could occurs above the shelf bathymetry. When the geostrophic coastal current is controlled by the baroclinic instability, the increase of the topographic parameter To yields a selection of smaller unstable wavelengths, which could be two or three times smaller than the one emerging in a flat bottom configuration. For larger values of To the growth rates of baroclinic modes are strongly dampened and the horizontal shear instability becomes the dominant one. The latter is then weakly affected by the shelf slope and leads to large unstable wavelengths. There are no large meanders or any eddy detachments when the topographic parameter reach finite values around To=-3 .
Moreover, for moderate To or when the current is slightly shifted off the shelf, we find that a secondary nonlinear processes may lead to smaller eddies. We exhibit here a new dynamical sequence, leading to the formation of sub meso scale structures over a steep shelf by splitting of mesoscale eddies. Hence, both the numerical and the experimental studies show that the bottom topography has a strong impact on the nonlinear saturation of unstable surface flows.



Surface vorticity field (red:cyclonic/blue:anticyclonic) obtained at t=22T for two distinct laboratory experiments: flat bottom (left panel) and slopped bottom (right panel) corresponding respectively to To=0 and To=-1.3

Turbulent water mass exchanges across the Antarctic continental slope

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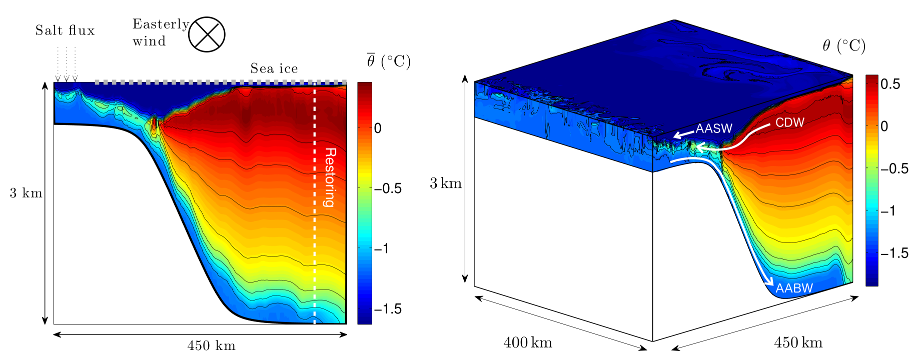
Water on the Antarctic continental shelf is largely shielded from the circulation of the open ocean by the Antarctic slope front (ASF), an almost-circumpolar feature that overlies the continental slope. Transport and mixing of water masses across the ASF play a key role in a range of physical and biogeochemical processes. Antarctic Bottom Water (AABW) formed on the continental shelf crosses the ASF as it sinks down the continental shelf, where it spreads and ventilates the abyssal ocean. Along certain stretches of the Antarctic coastline, Circumpolar Deep Water (CDW) intrudes onto the continental shelf, where it carries heat to the bases of marine-terminating glaciers and supplies nutrients to coastal phytoplankton assemblages.

This work explores the role of mesoscale and submesoscale turbulence in facilitating cross-slope exchanges of water masses at the Antarctic margins. Recent studies indicate that eddies can enable cross-slope exchanges via bolus transports and stirring along isopycnals. We present a recently-developed eddy-resolving process model of the Antarctic continental shelf and slope. The model enforces realistic offshore ocean stratification over idealized shelf/slope bathymetry, in order to provide a realistic representation of the water masses in a configuration that can be analyzed cleanly. The model forcing includes a westward wind stress over the continental slope and buoyancy loss on the continental shelf, consistent with prevailing Antarctic easterly winds and brine rejection in coastal polynyas.

We show that all of the shoreward transport of CDW, and a substantial fraction of the export of AABW, are achieved by eddies. Despite being suppressed by the strong topographic potential vorticity gradient, mesoscale eddies carry CDW across the continental slope at a rate comparable to the wind-driven shoreward Ekman transport of Antarctic surface waters (AASW). The CDW is then carried across the continental shelf by energetic submesoscale eddies, generated by buoyancy loss at the shoreward edge of the model domain. The eddies on the continental shelf and slope largely source their energy from baroclinic instability of the deep AABW layer as it descends to the deep ocean. This energy source is sensitive to variations in the model surface forcing and bathymetry, small changes in which can produce a substantial rearrangement of the water mass pathways and volume transports across the continental slope. These findings suggest that shoreward eddy transport of CDW should be localized to a few favorable locations around the Antarctic shelf break, and that future changes in the easterly wind strength or coastal polynya productivity could significantly alter the shoreward heat transport and the properties of the outflowing AABW.



(left) Configuration of our process model of the Antarctic continental shelf and slope. Contours show a snapshot of potential temperature from our reference simulation. (right) Three-dimensional snapshot of the potential temperature from our reference simulation, showing the whole domain. White labels/arrows indicate the main water masses and their cross-slope transports.

Eddy-topography interactions and the fate of the Persian Gulf Outflow

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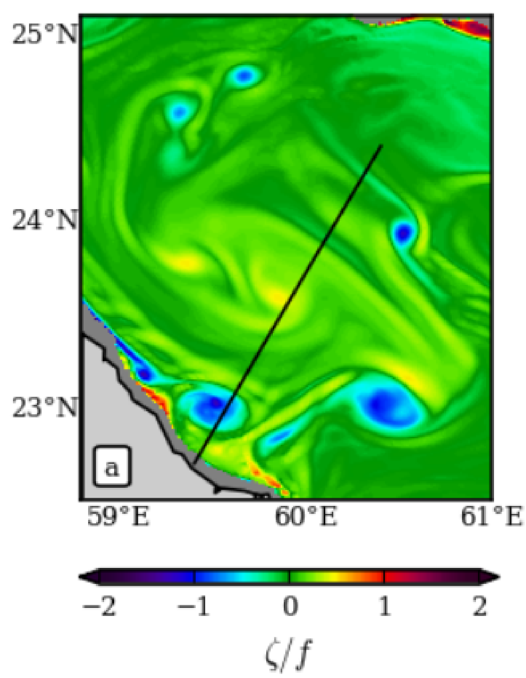
This modeling study addresses how the salty water flowing out of the Per- sian Gulf (Persian Gulf Water, PGW) is responsible for the smooth large-scale clima- tological salinity gradient observed in the Gulf of Oman. The spreading of saline PGW is a combined effect of mesoscale eddies and associated sub-mesoscale turbulence that in- volves eddy-topography interactions and frictional boundary layers. The circulation in the Gulf of Oman is dominated by the presence of mesoscale eddies that are formed re-motely and propagate into the Gulf. Because of the relative narrowness of the Gulf, these eddies interact with the boundaries and generate thin and intense boundary layers with high relative vorticity ($|\zeta/f| > 1$) that may detach from the slope. Once detached, shear instability causes the ribbons of relative vorticity to roll up into submesoscale coherent vortices (SCVs). These interactions with topography take place at intermediate depths that encompass the depth of the PGW slope current, which originates from the Strait of Hormuz and flows southwestward along the coast. After formation, the SCVs are ad- vected into the interior by the mesoscale eddies that are persistent in the Gulf of Oman. Since they trap PGW this results in a net offshore transport of intermediate saline wa- ter. The SCVs decay after a few days, due to the strong mesoscale deformation field, and relax their salt in the inner Gulf. A combination of realistic and idealized high res- olution primitive equation numerical simulations are used to separate the interactions of the relevant processes.



Vorticity at 200m in the Gulf of Oman showing the detachment of a boundary layer by a mesoscale eddy.

Resonant interactions including coastal waves and their role in transport and mixing

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We show how resonant wave interactions including coastal waves (Kelvin waves in the case of very steep topography, but also shelf and edge waves when steepness diminishes) influence transport and mixing in coastal zones. Two types of mechanisms are displayed and quantified in the simplest framework of layered shallow-water models: 1) phase-locking and resonance of coastal waves and other waves propagating on the background of coastal currents/density fronts leading to instabilities which generate, at the saturation stage, coherent structures with specific transport and mixing properties, 2) interactions between incoming free waves and trapped coastal waves, or between free waves and coastal currents, leading to resonant excitation of coastal waves which, at the nonlinear stage of their evolution either break and form zones of enhanced mixing (Kelvin waves) or form coherent structures with specific transport properties (edge and shelf waves). We also show how the presence of bathymetry modifies the instabilities of density currents and their saturatio patterns.