

Submesoscale Flows and Mixing in the Oceanic Surface Layer Using the Regional Oceanic Modeling System (ROMS)

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LONG-TERM GOALS

The long-term goals of this project are to further the insight into the dynamics of submesoscale flow in the oceanic surface layer. Using the Regional Oceanic Modeling System (ROMS), we aim to understand the impact of submesoscale processes on tracer mixing at small scales and the transfer of energy towards the dissipative scales of non-geostrophic turbulence. An advanced understanding of surface layer processes at these small scales is instrumental in interpreting remote and directly sensed observations that are increasingly capable of observing submesoscale flows. These goals accompany the continuation of the evolution of the Regional Oceanic Modeling System (ROMS) as a multi-scale, multi-process model and its utilization for investigations of a variety of oceanic phenomena ranging from from turbulence to basin-scale circulation.

OBJECTIVES

- Further development of the non-hydrostatic component of ROMS (Kanarska *et al.*, 2007) is required to increase its efficiency and generality. The non-hydrostatic ROMS involves the solution of a three dimensional Poisson problem for the non-hydrostatic pressure at each baroclinic time step. We are aiming to improve the numerical properties of the Poisson operator associated with the solution of non-hydrostatic processes with regards to solution efficiency, but also improve energy conservation and further reduce pressure gradient errors near topographic slopes.
- As the size of the grid scale is further reduced by either larger computational grids or successively nested domains, the need for further investigation of sub-grid scale parameterizations is necessary. The K-Profile Parameterization scheme (KPP; Large *et al.*, 1994) has been extensively used for many oceanic studies and for a wide range of applications. This is appropriate when the scales that are explicitly resolved by the model do not include the dominant mixing processes such as those induced by static instability and wind-driven mixing. For the computational regime where those processes can be partially, but not yet fully resolved, it will require the use of alternative subgrid-scale parameterizations.
- We aim to provide appropriate, physically relevant boundary conditions for our finest scale simulations. Our approach to obtain these is to continue the practice of computing eddy

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resolving basin scale solution and subsequently compute nested solutions down to the required scales.

- Our focus is on situations where mesoscale energy transfer exchange with submesoscale unbalanced motions is likely to occur. Our goal is to identify the regimes of submesoscale flows in the oceanic surface layer.
- In the context of the ONR DIR program; "Scalable Lateral Mixing and Coherent Turbulence", we aim to perform targeted simulations of the Northwestern Atlantic that are in direct support of observations in that area. The solutions will be used to test a variety of sampling strategies by performing virtual experiments using the numerical data. In this way, it is possible to test in advance whether features (such as, for instance, the relative vorticity field at a scale of 1 km) can be determined with a particular choice of observational strategy. Which strategy is preferred will depend on the phenomena studied and its associated spatial and temporal scales of coherency.

APPROACH

Computational simulation of oceanic currents and material distributions is an important and evolving tool in the geosciences. ROMS is a loosely coordinated modeling approach with a substantial international community of scientific developers and users (<http://www.myroms.org/>).

ROMS is a generalized terrain-following coordinate, primitive-equation oceanic model that is implemented as a modern, efficient parallel code, and it is accompanied by an infrastructure of pre-, post-processing, and visualization tools. ROMS provides a test-bed for some of the most innovative algorithms and parameterizations, and it probably is now the most widely used model among academic researchers for regional, high-resolution simulations of highly turbulent flows. We, at UCLA, are among the lead architects of ROMS (Shchepetkin and McWilliams, 1998, 2003, 2005, 2008, 2011). Our approach is problem-driven: the algorithmic formulation and code implementation are advanced to meet the requirements for simulating particular processes and phenomena.

As model changes are made through a sequence of problems, the capabilities of ROMS expand to make it a more robust simulation tool, encompassing a wider range of coupling linkages with the circulation physics.

Using our nesting capabilities, we are uniquely qualified to study phenomena that range in scales that are between boundary layer turbulence and mesoscale eddy flows. These type of phenomena are difficult to model because they require very high numerical resolution, but additionally, there is a need for a non-trivial mesoscale flow to provide the lateral tracer gradients and velocity straining fields required to provide a realistic environment in which these oceanic phenomena exist. We have fine-tuned a computational approach that relies on multi-leveled nested solutions to arrive at this flow regime, which has been elusive for modelers until now.

WORK COMPLETED

Over the duration of the project, we have successfully completed detailed realistic simulations of several local regions in the Atlantic as well as the Pacific Ocean. Using the nested computational approach described above, we have computed high resolution solutions (down to $dx = 150$ m grid resolution) in the Brazil Current near Rio de Janeiro, the Gulf Stream, both upstream and downstream of the separation point at Cape Hatteras, in the Kuroshuo Current System near Japan, and the

Solomon Sea in the South West Pacific. We have advanced our suite of diagnostic tools, using a Python-Fortran hybrid approach. A new off-line Lagrangian float tracking tool was implemented that was used extensively to detect and quantify mixing events. Using particle tracking backwards in time, it was used to verify the origin of water masses. We have also made important progress on the study of the role of pressure in the presence of topographic features. In a series of simulations of flows past idealized features such as Gaussian Seamounts, we are examining the boundaries of numerical reliability of the standard formulation of ROMS by comparison to alternative approaches such as used by the MITgcm model and a new class of boundary-fitted numerical discretizations. We have implemented a new non-hydrostatic model using terrain following coordinates and have laid bare the root cause of pressure gradient errors in a wide class of numerical models. This is the final report for this grant.

RESULTS

We present a few highlights for this project. The publications list provides a view of the finalized results across all our ONR modeling projects from 2012-2014, the period of this grant.

Submesoscale Cold Filaments in the Gulf Stream: A set of realistic, very high resolution simulations have been computed for the Gulf Stream region to study the life cycle of the intense submesoscale cold filaments that form on the subtropical gyre interior wall of the Gulf Stream. The surface buoyancy gradients and ageostrophic secondary circulations intensify in response to the mesoscale strain field as predicted by the theory of filamentogenesis. There is a intensification of the secondary circulation due to an additional process at the center of a cold filament. Filament dynamics in the presence of a mixed layer is not adequately described by the classical thermal wind balance. The effect of vertical mixing of momentum due to turbulence in the surface layer is of the same order of magnitude as the pressure gradient and Coriolis force and contributes equally to a so-called turbulent thermal wind balance (TTW). Filamentogenesis is disrupted by vigorous submesoscale instabilities. The cause of the instability is the lateral shear as energy production by the horizontal Reynolds stress is the primary fluctuation source during the process; this contrasts with the usual baroclinic instability of submesoscale surface fronts. Diabatic mixing is strong as parcels move across the filaments and downwell into the pycnocline. The life cycle of a filament is typically a few days in duration, from intensification to instability to dissipation (Fig. 1). These results are reported in Gula *et al.*(2014).

Frontal Eddies on the Shelf Break Upstream of Cape Hatteras: Frontal eddies are commonly observed and understood as the product of an instability of the Gulf Stream along the Southeastern U.S. seaboard. We have addressed the finite-amplitude behavior of a frontal eddy after formation as a cut-off meander over the Charleston Bump, including its structure, propagation, and emergent submesoscale interior and neighboring substructure, as simulated in very high resolution simulations ($dx=150m$) of the Gulf Stream along the Southeastern U.S. seaboard. A very rich submesoscale structure is revealed inside the frontal eddy. Meander-induced frontogenesis sharpens the gradients and triggers submesoscale barotropic shear instability on the rim of the eddy (Fig. 2). The small scale meandering perturbations evolve into rolled up vortices that are advected into the interior of the frontal eddy. The frontal eddy also locally creates a strong southward flow against the shelf leading to boundary generation of negative potential vorticity and subsequent centrifugal instability. Virtual Lagrangian particles have been used to illustrate and quantify the impact of a frontal eddy in trapping material, generating cross-shelf exchanges and in mixing tracer properties.

Submesoscale Instabilities and Mixing on the Gulf Stream North Wall: Realistic very high resolution simulations ($dx = 150m$) of the Gulf Stream North Wall have been performed during wintertime using the ROMS model. Submesoscale structures associated with the strong lateral density gradients of the North Wall are seen in the form of deep filaments detraining warm salty water from the Gulf Stream ("streamers"), and cold water intrusions due to submesoscale instabilities in the mixed-layer ("comma instabilities"): Fig. 3. Both processes were successfully sampled during the 2012 LatMix field campaign so we have been able to compare modeling results with in-situ observations and use the modeling results to explain the formation, dynamics, and role in driving exchanges across the front. The comma instability is shown to be driven by the release of potential energy through mixed layer baroclinic instabilities. The instability predominantly occurs on the upstream faces of the Gulf Stream meanders. A process of North Wall frontogenesis and surface convergence functions as a strong stabilizing agent on the downstream sides of the large scale meanders. Using virtual Lagrangian floats in our model solutions we have investigated their quantitative effects in lateral and vertical mixing. By tracing these floats backwards in time, we have identified the source of the different water masses in the region and explained how all these processes act on mixing cold fresh water from the north with the hot salty Gulf Stream water to form the "18 Water".

Statistics of Submesoscale Turbulence: Following a series of tests of observational strategies to observe submesoscale turbulence statistics, a detailed view of upper ocean vorticity, divergence, and strain statistics was obtained by a two-vessel survey in the North Atlantic Mode Water (NAMW) region in the winter of 2012. Synchronous Acoustic Doppler Current Profiler (ADCP) sampling provided the first in situ estimates of the full velocity gradient tensor at $O(1\text{ km})$ scale without the usual mix of spatial and temporal aliasing. The observed vorticity distribution in the mixed layer was markedly asymmetric. Skewness of the vorticity distribution decreased linearly with depth, disappearing completely in the pycnocline.

The model predictions match the mixed layer observations of distributions of vorticity, divergence, and strain rate very well (Fig. 4). However, below the mixed layer observed distributions were wider than their model counterparts. The observed gradual decrease of relative vorticity skewness with depth was qualitatively similar to the numerical results, but the change of sign of vorticity skewness at 250 – 350 m depth predicted was not visibly present in our observations. Discrepancies between the model and observations in the upper pycnocline can be attributed to the underrepresentation of inertia-gravity waves (IGW) by the model and to the reduced signal-to-noise ratio in the deeper ADCP data. In the mixed layer, the model reproduces observed velocity spectra well but in the upper pycnocline, the model spectra are 510 times less energetic at scales 20 km, indicating a deficiency of short IGW. The model forcing does not include high-frequency wind stress variations or tides, the two major sources of internal wave energy, and has a relatively coarse grid resolution (with respect to the wave spectrum). The observed near-surface vorticity distribution in the NAMW region in winter was substantially more asymmetric than that found in previous submesoscale observations. LatMix observations were in excellent agreement with numerical model predictions for active submesoscale turbulence in this region. These results have been reported in Shcherbina *et al.* (2013).

Topographic Vorticity Generation and Inertial Instability in the Gulf Stream: There is strong topographic vorticity generation on both sides of the Gulf Stream as the flow moves through the Florida Straits. The cyclonic shear is amplified by bottom drag along the Florida coast and releases its energy through horizontal Reynolds stress when the flow moves away from the slope in the form of a

street of submesoscale vortices. There is strong anticyclonic vorticity generation on the eastern side of the Gulf Stream against the Bahamas Islands (Fig. 5). This leads to sustained negative vorticity generation. Strong negative values of potential vorticity lead to inertial instability after topographic release, and formation of anticyclonic vortices. The sequence is much like the anticyclonic events in the California Undercurrent (Molemaker *et al.*, 2014; Dewar *et al.*, 2014). This process is likely to be generic for boundary slope currents moving cyclonically around a basin, generating strong vertical vorticity within the bottom boundary layer, subsequently separating over complex topography, and giving birth to coherent anticyclonic vortices.

Submesoscale Characteristics and Origins in the Southwest Pacific: High-resolution solutions are used to characterize the mesoscale and submesoscale variability in the Solomon and Coral Seas (Hristova *et al.*, 2014). Both regions are characterized by high surface submesoscale variance in the form of fronts, filaments, and coherent vortices (Fig. 6). The Coral Sea is dominated by submesoscale frontal instabilities on lateral buoyancy gradients that are forced by mesoscale strain fields. These structures catalyze energy dissipation for the large-scale circulation and are responsible for a large part of the vertical fluxes of mass, buoyancy, and materials in the upper ocean layers. The Solomon Sea is different, in the sense that it has less seasonal variability of the submesoscale and has a significant additional source of submesoscale gradients due to strong topographic and boundary interactions. A new set of simulations has been computed to assess the seasonal variability of the submesoscale and the effect of tidal flows at even higher horizontal spatial resolutions.

Filament Frontogenesis by Boundary Layer Turbulence: A submesoscale filament of dense water in the oceanic surface layer can undergo frontogenesis with a secondary circulation that has a surface horizontal convergence and downwelling in its center (Fig. 7). This secondary circulation occurs either due to mesoscale straining deformation or due to the surface boundary layer turbulence that causes vertical momentum mixing. In the latter case the circulation approximately has a linear horizontal momentum balance among the baroclinic pressure gradient, Coriolis force, and vertical momentum mixing, *i.e.*, a turbulent thermal wind. The frontogenetic evolution induced by the turbulent mixing sharpens the transverse gradient of the longitudinal velocity (*i.e.*, it increases the vertical vorticity) through convergent advection by the secondary circulation. In an approximate model based on the turbulent thermal wind, the central vorticity approaches a finite-time singularity, and in a more general hydrostatic model (ROMS), the central vorticity and horizontal convergence amplify by shrinking the transverse scale to near the model's grid resolution limit within a short advective period on the order of a day (McWilliams *et al.*, 2014). This process commonly helps maintain sharp submesoscale filaments in realistic computational simulations and in nature.

IMPACT/APPLICATIONS

Geochemistry and Ecosystems: An important community use for ROMS is biogeochemistry: chemical cycles, water quality, blooms, micro-nutrients, larval dispersal, biome transitions, and coupling to higher tropic levels. We collaborate with Profs. Keith Stolzenbach (UCLA), Curtis Deutsch (UCLA), David Siegel (UCSB), and Yusuke Uchiyama (Kobe).

Data Assimilation: We collaborate with Dr. Zhinjin Li (JPL) and Prof. Kayo Ide (U. Maryland) by developing model configurations for targeted regions and by consulting on the data-assimilation system design and performance. Current quasi-operational, 3DVar applications are in California (SCCOOS and CenCOOS) and in Alaska (Prince William Sound).

TRANSITIONS

ROMS is a community code with widespread applications (<http://www.myroms.org>).

RELATED PROJECTS

Three Integrated Ocean Observing System (IOOS) regional projects for California and Alaska (SCCOOS, CenCOOS, and AOOS) are utilizing ROMS for data assimilation analyses and forecasts.

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FIGURES

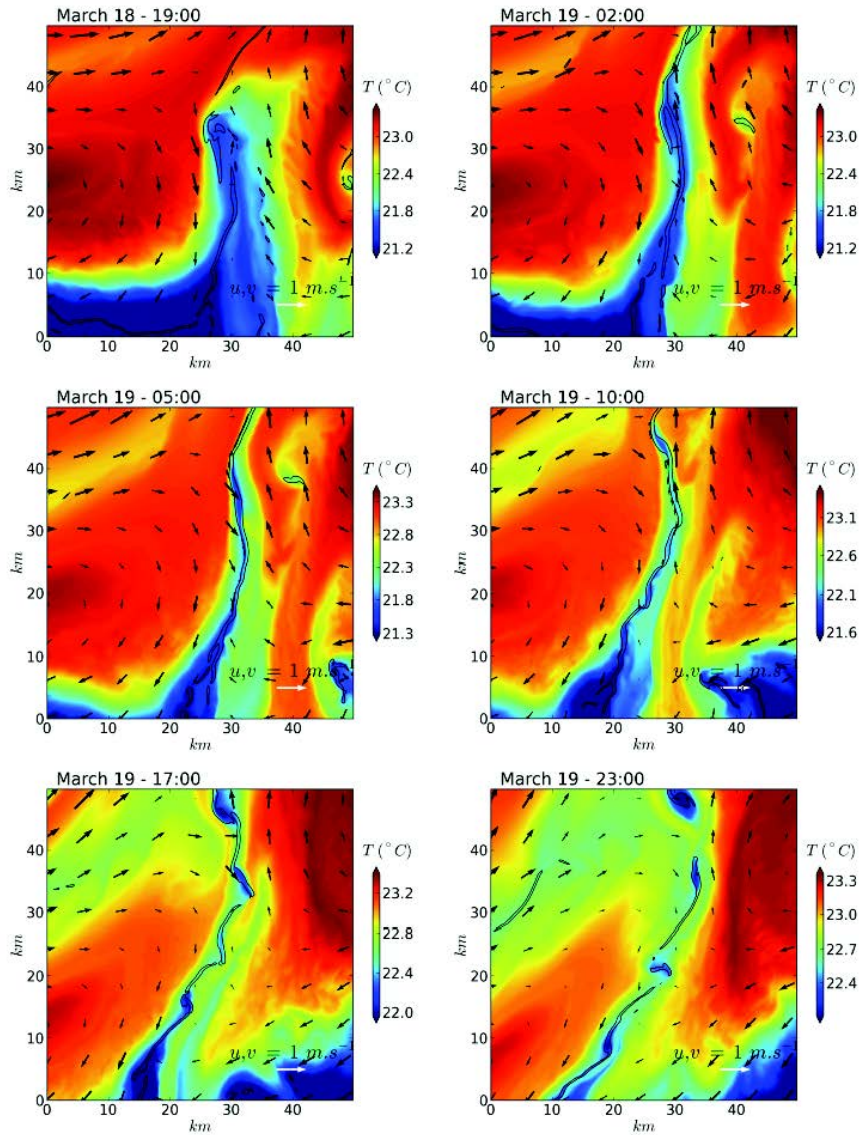


Figure 1: SST (in colors), surface relative vorticity (black contours) and surface velocity (vectors) for the evolution of a cold filament in the winter time Gulf Stream, upstream of Cape Hatteras. The vectors show the horizontal velocity anomalies for the domain shown. Note the initial sharpening of the cold filament after which the onset of a shear driven instability limits the filament frontogenetic process. The total life cycle of sharpening, instability and breakdown takes place in about 24 hours.

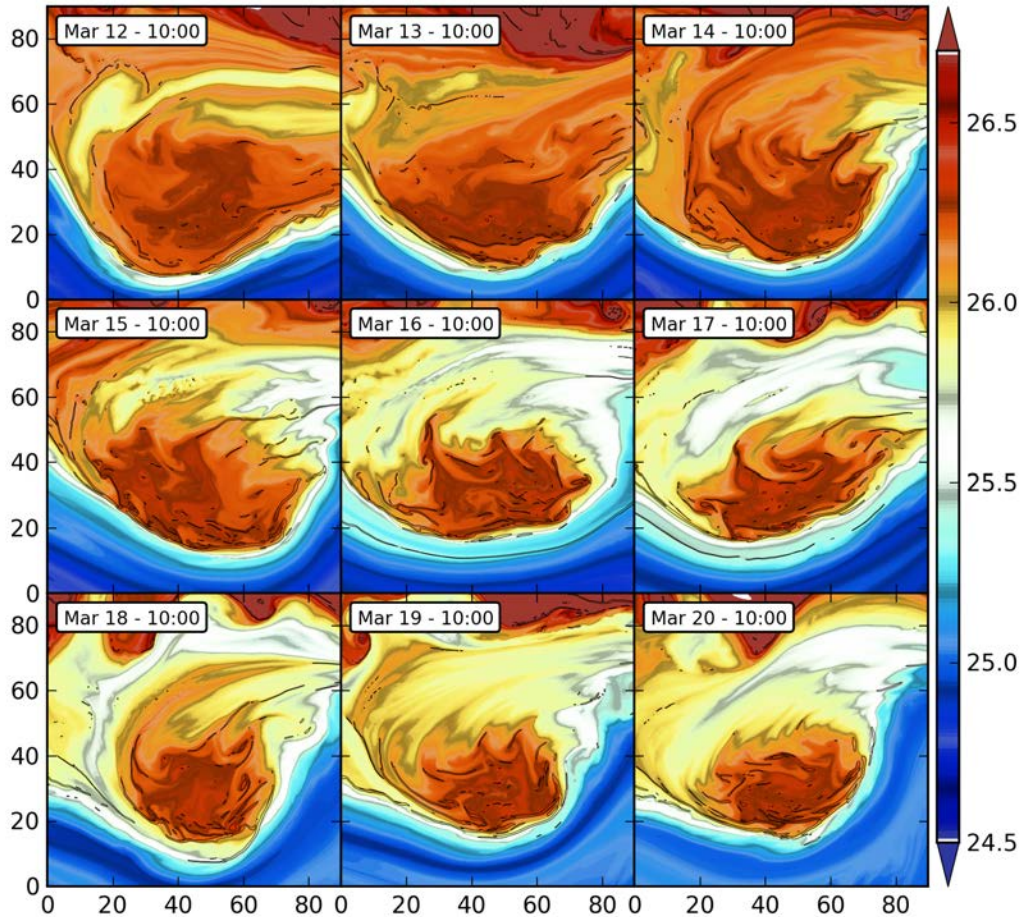


Figure 2: *Snapshots of surface density (in kg m^{-3} , colors) and relative vorticity (at $\pm 2f$ in black contours) at a 3 hours interval showing the propagation of a Gulf Stream frontal eddy along the South Atlantic Bight in the region south of the Gulf Stream separation point at Cape Hatteras. Submesoscale vortical structures can be seen forming in the interior of the slope eddy, while the sharp front and strong vorticity values on the edge indicate submesoscale strain-induced frontogenesis.*

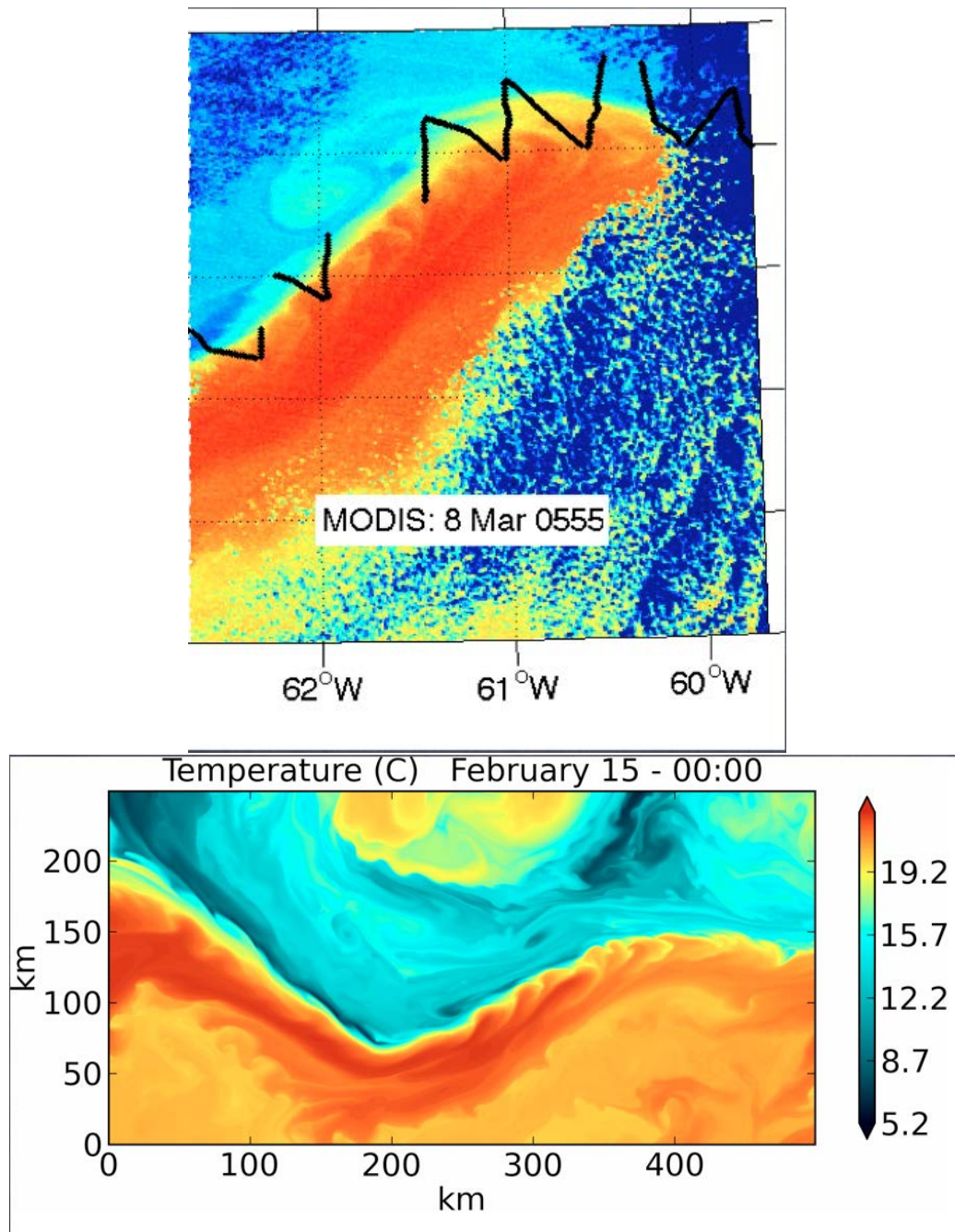


Figure 3: *Upper panel: SST as observed by the MODIS satellite on March 8, 2012. Partial ship tracks of LatMix observations are shown as solid black lines. Visible in the image are the comma like cold surface intrusions. Lower panel: Numerical simulation of a winter time Gulf Stream. SST shows the emergence of comma instabilities on the North Wall. Analysis shows these instabilities to be driven by surface mixed layer baroclinic instabilities. Lagrangian particle releases reveal that these instabilities may be a significant source of cross North Wall mixing and a potential alternate source of 18 degree mode water.*

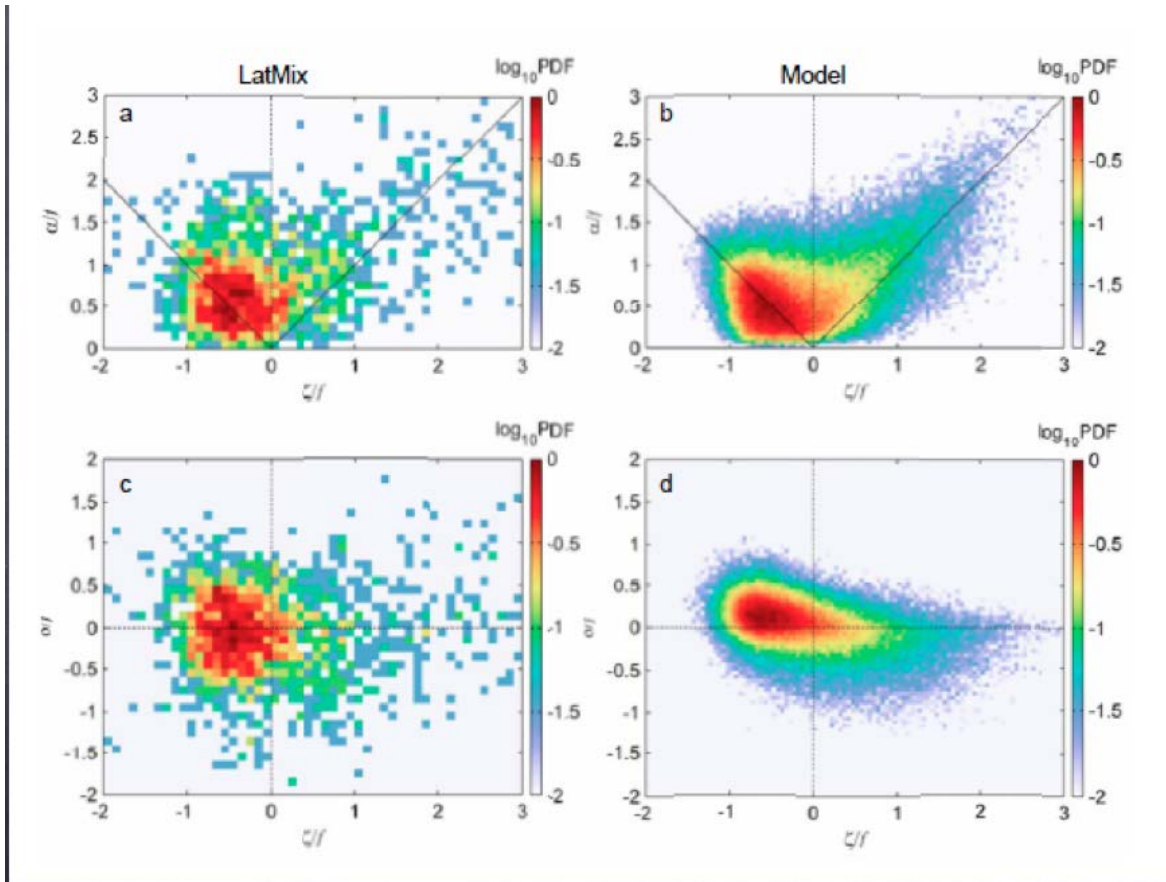


Figure 4: *Joint probability distribution functions (JPDFs) of (a, b) vorticity and strain rate and (c, d) vorticity and divergence in the mixed layer (050 m) based on LatMix 300 kHz ADCP observations (Figures 5a and 5c) and ROMS (Figures 5b and 5d). Black dotted lines in Figures 5a and 5b correspond to one-dimensional shear flow; horizontal axes correspond to solid body rotation. All JPDFs are normalized by their maximum values. (From Shcherbina et al., 2013)*

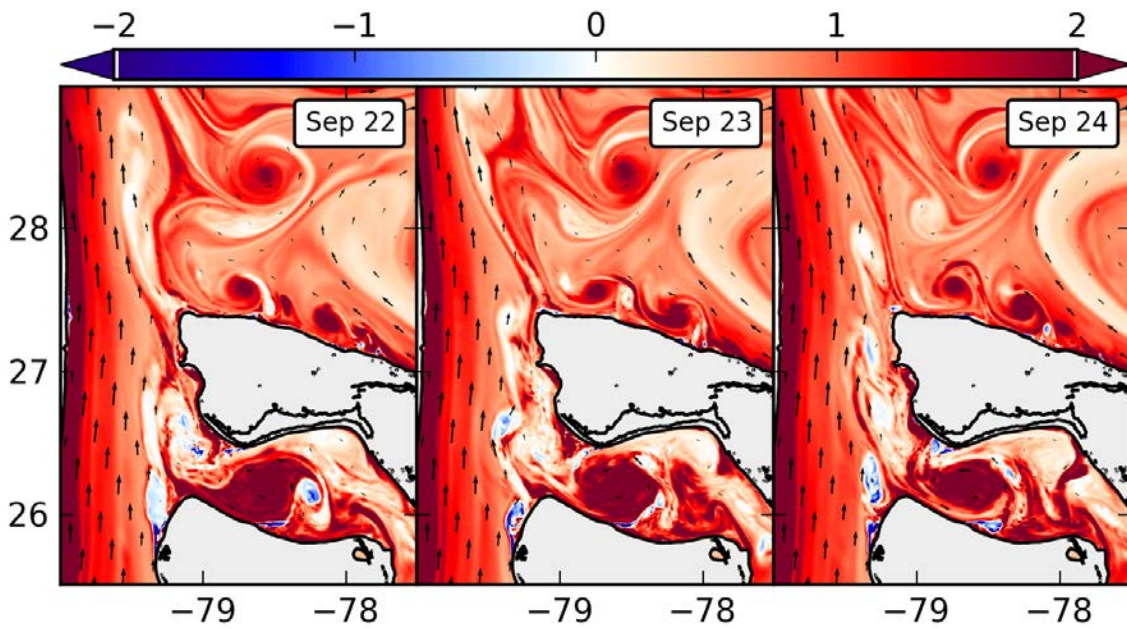


Figure 5: *Snapshots of potential vorticity [m^2s^{-4}] in the Gulf Stream at $z = -100$ m for the indicated latitude and longitude ranges. Strong negative values of PV are generated by the bottom drag along the Bahamas slope and lead to inertial instability after topographic release, and formation of anticyclonic vortices. The instability produced-vortices have limited lifetimes and upscaling because of the strong deformation in the high shear and strain regions of the Gulf Stream.*

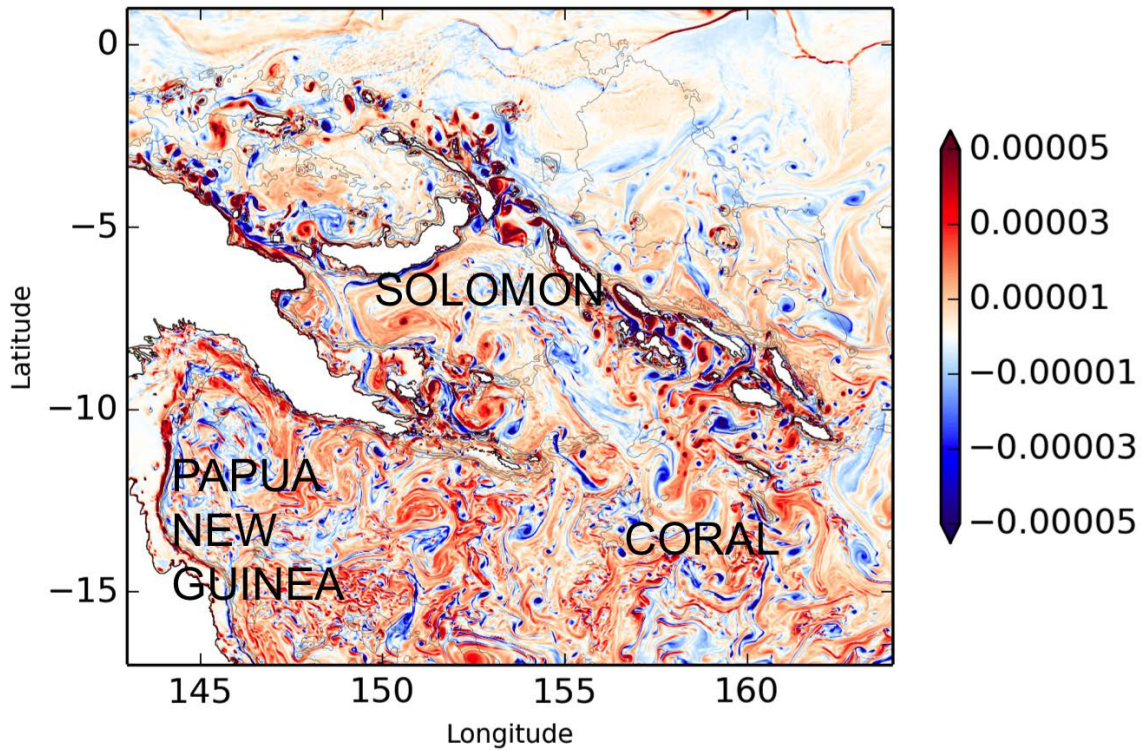


Figure 6: *Surface relative vorticity [s^{-1}] in the Southwest Pacific showing a rich surface submesoscale field of fronts, eddies and filaments. In addition to the known mechanism of submesoscale generation by means of frontal instabilities, the interaction of the flow with boundaries are a significant source of small scale vorticity wakes.*

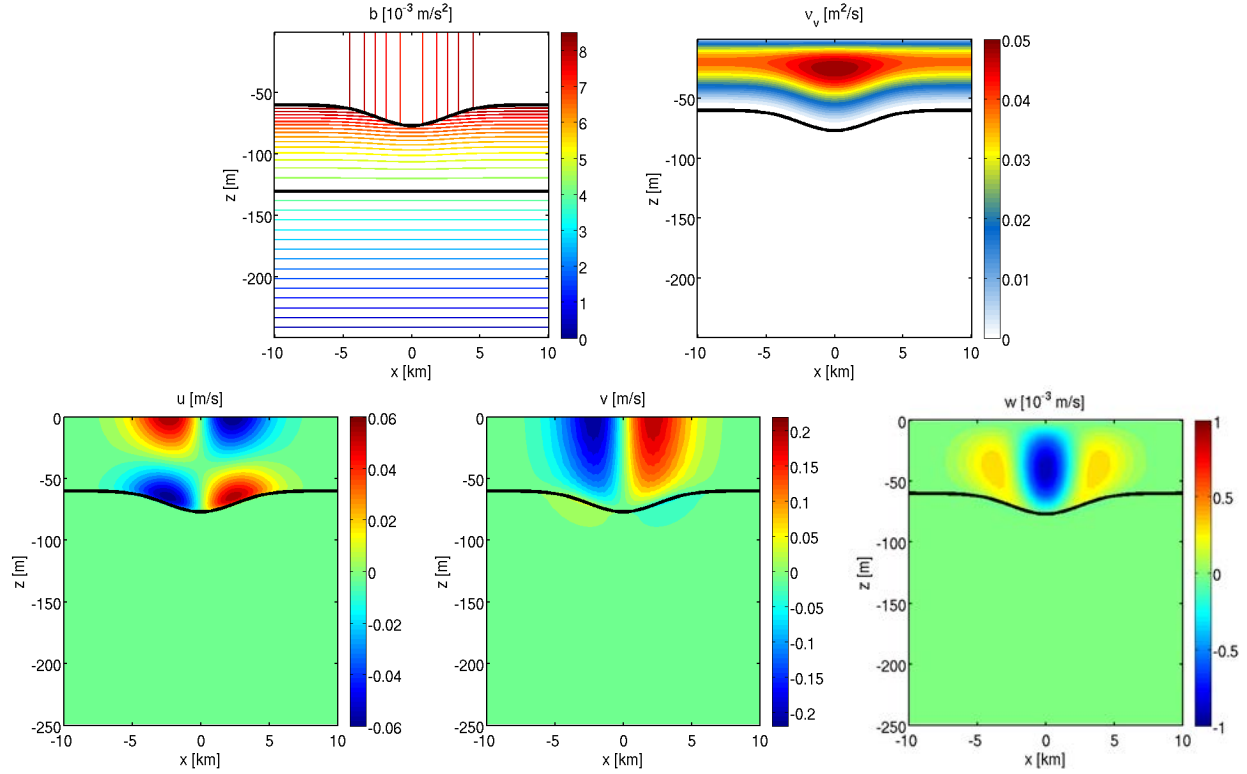


Figure 7: *Buoyancy, vertical eddy viscosity (from the K-Profile Parameterization scheme), and (across, along, vertical) velocity fields for an idealized submesoscale filament that satisfies a turbulent thermal wind balance. The black line denotes the boundary layer depth at $z = h(x)$. Due to the horizontal convergence at the surface in the center, when these fields are used as an initial conditions in ROMS with the K-Profile Parameterization for $\nu_v(x)$, the velocity gradient, $\partial v/\partial x$, frontogenetically increases very rapidly. Results are from McWilliams *et al.*(2014).*