Isopycnal Transport and Mixing of Tracers by Submesoscale Flows Formed at Wind-Driven Ocean Fronts

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LONG-TERM GOALS

This project is part of the DRI on Scalable Lateral Mixing and Coherent Turbulence that aims to characterize lateral mixing in the ocean on scales of 10m-10 km, the submesoscales. Lateral mixing at the submesoscales is not accounted for in present-day ocean models. This deficiency is a potential source of error in the numerical prediction of the distribution of temperature, salt, nutrients, phytoplankton, pollutants, etc. in the upper ocean. The goal of the DRI is to develop parameterizations for submesoscale processes to improve the simulation of lateral mixing in ocean models.

OBJECTIVES

Winds blowing along ocean fronts are highly effective at energizing flows on the submesoscale. The process involves three stages: a frontal mixing stage where small scale gravitational and symmetric instabilities homogenize properties in the mixed layer, a subduction phase where three-dimensional baroclinic mixed layer instabilities exchange fluid along isopycnal between the mixed layer and pycnocline, and a phase in which the mixed layer instabilities evolve into coherent vortices that drive lateral stirring along surfaces of constant density. The objective of this research is to characterize and parameterize the submesoscale physics involved in each of these steps and evaluate the lateral mixing characteristic of the flows in each stage. Dynamical insights gained from the research will be used for planning, interpreting, and analyzing observations collected during the two field programs that will be conducted as part of the DRI.

APPROACH

The approach taken in this project is to use process-oriented numerical experiments of wind-driven submesoscale flows to study the governing physics of these flows. Analysis and diagnostics of these simulations combined with theory will be used to construct parameterizations for coarser resolution numerical models that cannot explicitly resolve the submesoscale.

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WORK COMPLETED

In this first year of the project numerical experiments designed to study the frontal mixing and subduction stages under forcing by steady winds have been performed. The simulations were run using the ROMS model with the configuration shown in Figure 1.

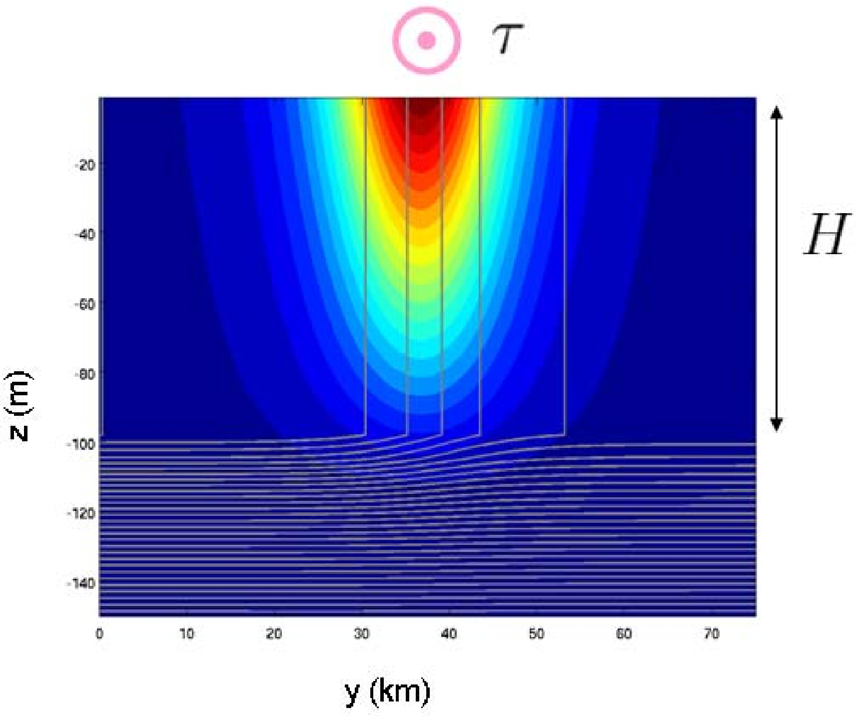

Fig. 1. Model configuration of the simulations. The initial condition for the density and the along-front velocity is shown in contours and shades respectively. A front outcrops into a mixed layer of thickness H, bounded below by a pycnocline. The simulations are forced by a steady wind-stress τ in the along-front direction.

Two sets of simulations were performed, the first aimed at studying frontal mixing by symmetric instability, the second focused on subduction and tracer transport by wind-forced baroclinic mixed layer instabilities. The second set of simulations has been performed and analyzed in collaboration with John Taylor and Raf Ferrari from MIT.

Apart from running these numerical simulations, I have been collaborating with Eric D’Asaro and Craig Lee (UW/APL) using the results of these simulations to interpret the observations that they collected at the Kuroshio Front as part of the AESOP project in which they observed enhanced mixing and dissipation during periods when the Kuroshio was unstable to symmetric instability. In addition to this work, Craig and Eric along with Raf Ferrari (MIT) and myself have been looking into the Gulf Stream separation point off of Cape Hatteras as a potential field site for the two observational programs of the DRI. We found that the currents in the region offer a range of the flow characteristics needed to test the full set of DRI hypotheses, all within a spatial domain small enough to be accessed during a single cruise. Our findings are summarized in a document that we have circulated to the other PIs in the DRI.

RESULTS

Winds blowing in the direction of geostrophic currents input energy into the ocean circulation. When those currents are baroclinic and surface intensified (such as shown in Fig. 1), winds of this orientation (i.e. down-front winds) drive Ekman flow that advects denser water over light lowering the potential vorticity in the mixed layer to negative values and making the flow susceptible to symmetric instability (SI). High-resolution, two-dimensional (i.e. invariant in the x-direction) numerical simulations show how this occurs (Fig. 2).

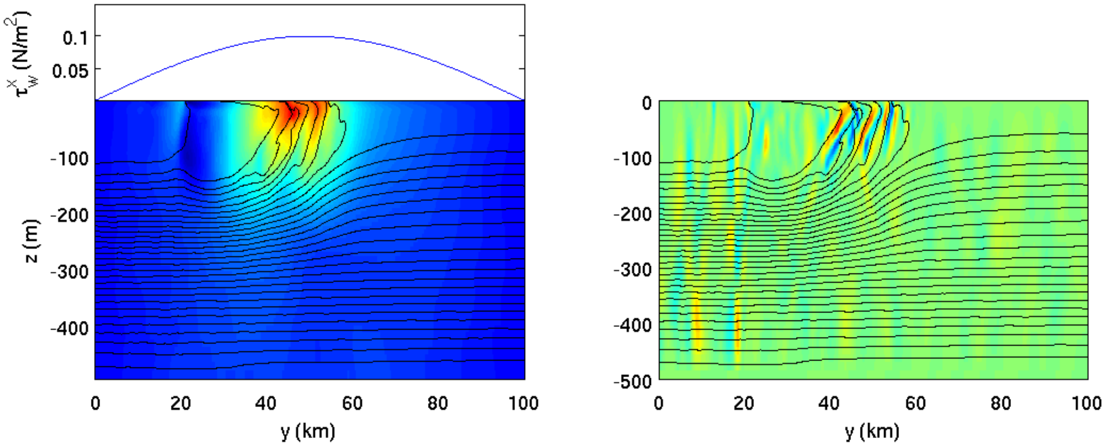

Fig. 2: A down-front wind-stress (upper left panel) drives a southward Ekman flow that advects denser water over light, generating near-surface inversions in the denisty field (contours). This triggers symmetric instability (SI) in the mixed layer whose vertical velocity (right panel) is characterized by 1-2 km wide overturning cells that run nearly parallel to isopycnals. Advection of momentum by SI distorts the zonal velocity (left panel) in such a way as to extract energy from the geostrophic flow. SI mixes both momentum and tracers along the isopycnals that outcrop at the front.

SI is a submesoscale shear instability that draws its energy from baroclinic, geostrophic currents. Forced SI driven by down-front winds extracts energy from the geostrophic flow at a rate that depends on the strength of the wind-stress and the change in the geostrophic flow over the thickness of the mixed layer, Δu_g. The kinetic energy going into SI is ultimately dissipated. In this way a fraction of the wind work on baroclinic, geostrophic currents is dissipated locally in the mixed layer and not available to accelerate the general circulation. The numerical simulations reveal that the fraction of wind-work dissipated by SI depends on the ratio of Δu_g to the value of the geostrophic flow at the surface, u_g^s (Fig. 3).

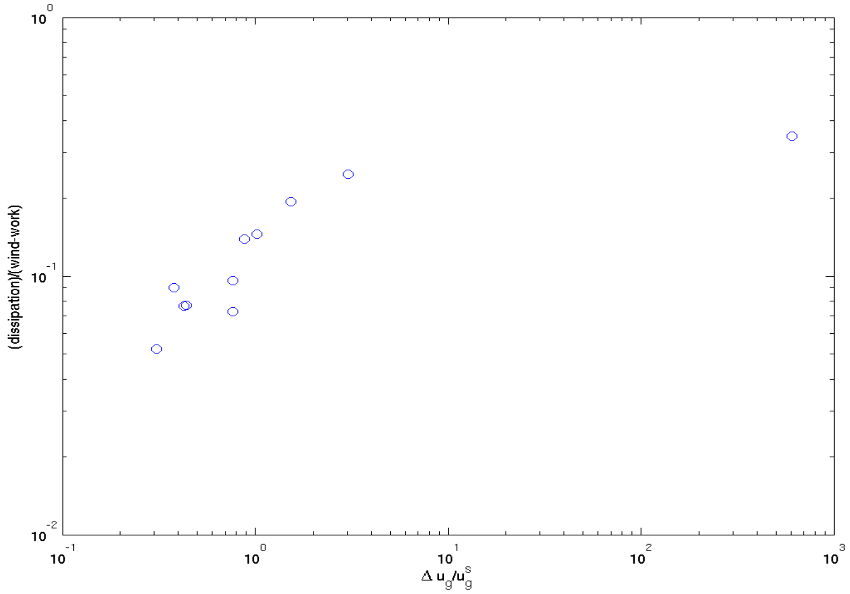

Fig. 3: The fraction of the total wind-work that is dissipated by forced SI increases with the ratio of the change in geostrophic flow over the mixed layer to the surface geostrophic velocity, $\Delta u_g / u_g^s$**.**

For baroclinic currents confined to the mixed layer,.up to 15-20% of the wind-work can be dissipated by SI.

These findings have been used to interpret the observations of the enhanced dissipation at the Kuroshio Front. The observations were made during a period of down-front winds when the potential vorticity at the front was negative and the hence the flow was susceptible to SI. Thus the inerpretation is that forced SI was responsible for the enhanced dissipation at the front. An analysis of the observations is currently underway to quantify the dependence of the enhanced dissipation on the wind-stress and Δu_g.

A second set of numerical experiments designed to study subduction and the isopyncal tranport of tracers at wind-forced fronts was performed using the configuration shown in Fig. 1. The simulations were fully three-dimensional. As in the 2D expeirments, the winds were down-front, and hence advection of density by the Ekman flow lead to a steepening of isopycnals at the front. Frontal baroclinic instabilities develop that release available potential energy, generating meanders and subducting surface waters along outcropping isopycnals (Fig. 4).

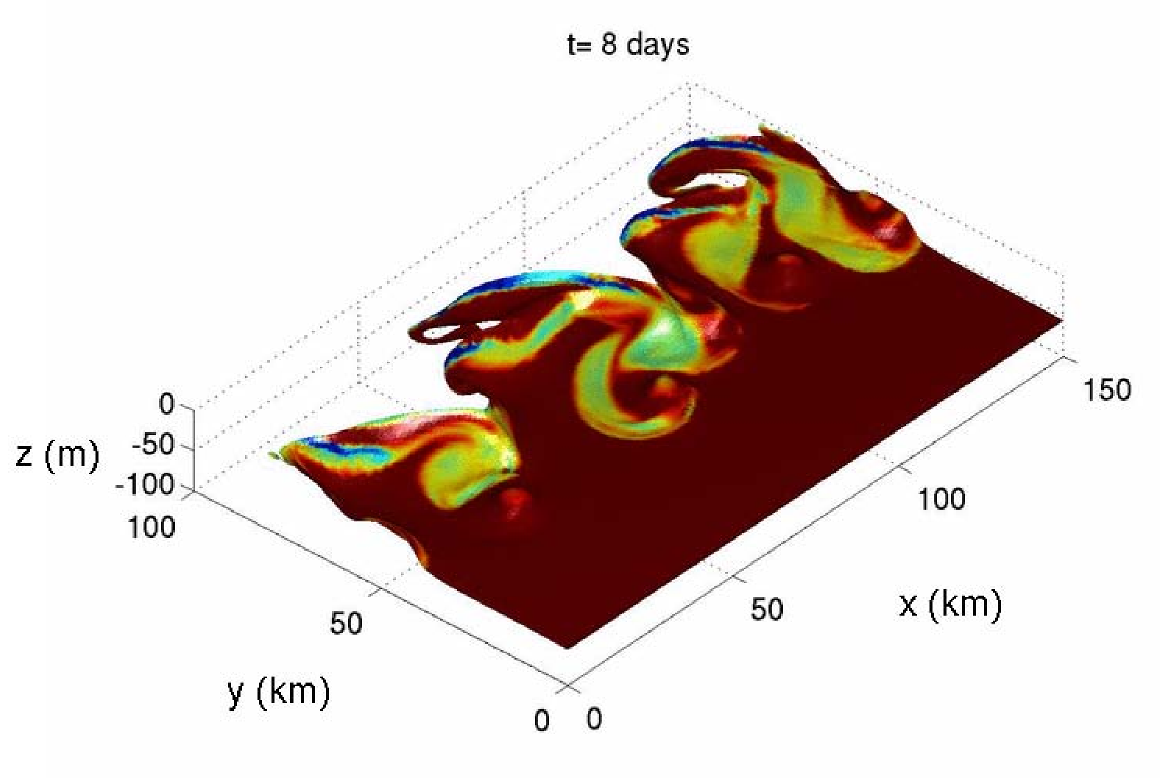

Fig. 4: Snapshot of the three dimensional structure of an isopycnal that outcrops at a front forced by a wind-stress blowing in the +x-direction, and the potential vorticity on that isopycnal (shades). Baroclinic frontal instabilities form that subduct low PV surface waters (shaded in blue-green) into the interior while upwelling water from the pycnocline (red shades) thus facilitating the transport of fluid along isopycnals.

The figure illustrates the way in which the frontal instabilities exchange water between the surface mixed layer and the pycnocline. On the downstream (upstream) side of a meander, low (high) PV water is subducted (upwelled) and pushed to the south (north) by the eddying motions. Low (high) PV water is associated with weak (high) stratification and a larger (smaller) vertical distance h in between isopycnals. Thus a correlation develops between isopycnal thickness and meridional velocity anomalies, inducing an eddy-induced transport velocity $v^* = \overline{v'h'}/\overline{h}$ (the overline and primes denote an *x*-average and deviation from that average, respectively) that is southward at the base of the front. It is this eddy-induced transport velocity that is responsible for the along isopycnal transport of tracers by submesoscale instabilities and hence is a key quantity to be parameterized.

It is convienent to express the eddy-induced transport velocity in terms of a streamfunction, i.e. $v^* = -\partial\psi_e/\partial z$. The eddy-induced streamfunction was diagnosed for all of the experiments. The structure of the streamfunction for one of the runs is shown in figure 5. It is characterized by an overturning cell centered at the front with a vertically sheared meridional flow that tends to restratify the mixed layer. This reflects the tendency of the baroclinic instabilities to release the available

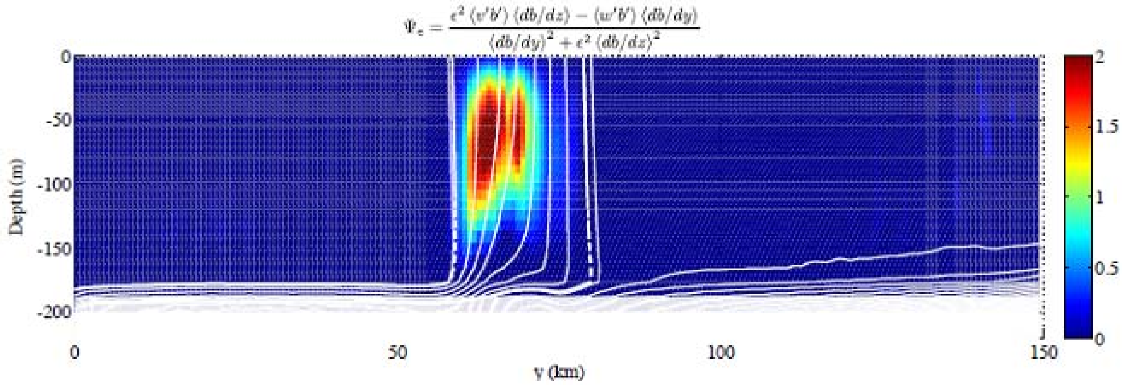

Fig. 5: The eddy-induced streamfunction ψ_e associated with baroclinic mixed layer instabilities (shades) and the zonally averaged density (contours). The eddy-induced transport velocity $v^* = -\partial \psi_e / \partial z$ is northward (southward) at the top (bottom) of the mixed layer and tends to restratify the mixed layer in opposition to the southward Ekman flow that reduces the stratification.

potential energy at the front and flatten isopycnals. The Ekman flow on the otherhand tends to steepen isopycnals, thus there is a competition between the Ekman and eddy-driven flows in setting the stratification of the mixed layer and the transport of tracers. Which flow dominates depends on their relative strengths. The strength of the Ekman flow is set by the Ekman transport $\tau/(\rho f)$. Fox-Kemper et al (2008) found that the magnitude of ψ_e for mixed layer instabilities that develop at fronts not forced by winds scales with the quantity $C_e |\nabla_h b| H^2 / f$, where $|\nabla_h b|$ is the horizontal buoyancy gradient of the front, H is the mixed layer depth, $C_e = 0.06$ is an efficiency factor, and f is the Coriolis parameter. It was an open question as to whether this scaling held for instabilities that develop at fronts forced by winds. To answer this question a set of 31 experiments were peformed where the strength of the Ekman transport and $C_e |\nabla_h b| H^2 / f$ were varied and the strength of the streamfunction diagnosed. The results of the experiments are summarized in Fig. 6. The figure shows that the scaling for the eddy-induced streamfunction does indeed hold for fronts forced by winds. The simulations also reveal that the Ekman and eddy-induced flows are of comparable strength when the parameter $r = \tau / \rho C_e |\nabla_h b| H^2$ lies between 2-4, while for higher (lower) r values the wind-driven (eddy-driven) circulation dominates the transport of water and tracers at mixed layer fronts.

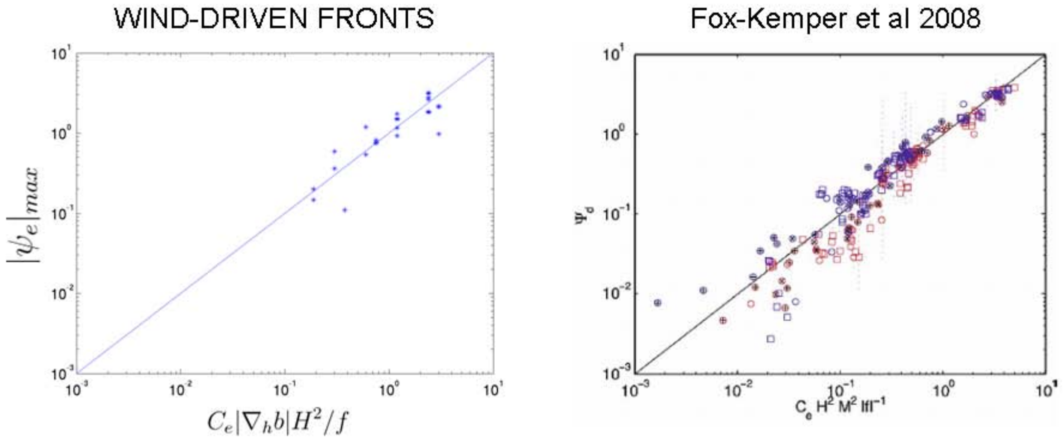

Fig. 6: Scatter plot of the maximum value of the eddy-induced streamfunction to the scaling for ψ_e: $C_e|\nabla_h b|H^2/f$ for fronts forced (left) and not forced by winds (right).

IMPACT/APPLICATIONS

The results of these numerical experiments impact our understanding of the energetics of the ocean circulation and how surface waters are transferred into the ocean interior. One of the fundamental questions in physical oceanography is how the wind-work on the ocean is dissipated. The results of these simulations suggest that dissipation by symmetric instability integrated over the worlds oceans could significantly reduce the amount of the wind-work available for accelerating the large-scale circulation, with the implication that this submesoscale phenomenon could play an integral role in setting the magnitude of the global circulation.

The second set of experiments reveal that baroclinic mixed layer instabilities can transport surface waters into the ocean interior at a rate that is comparable to the wind-driven Ekman transport at fronts with parameters typical of those observed at the Kuroshio, Gulf Stream, and the Antarctic Circumpolar Current. Accounting for this submesoscale process in coarse resolution ocean models will have an impact on the skill of the models in predicting the distributions of tracers in the upper ocean and the structure of the mixed layer.

REFERENCES

Fox-Kemper, B, R. Ferrari, and R. W. Hallberg, 2008a: Parameterization of mixed layer eddies. Part I: Theory and diagnosis. *J. Phys. Oceanogr.*, **38,** 1145–1165.