2010 Annual Report for Project on 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 a combination of theory and process-oriented numerical experiments of wind-driven submesoscale flows to study the governing physics of these flows. Analysis and diagnostics of these simulations 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 second year of the project numerical experiments designed to study the frontal mixing stages under forcing by steady winds have been performed. The simulations were run using the ROMS model and with a large eddy simulation (LES) which was performed in collaboration with John Taylor (MIT). The simulations that were performed were aimed at studying frontal mixing by symmetric instability (SI) and its impact on the energetics of the ocean circulation. The work has been published in Geophysical Research Letters (e.g. Thomas and Taylor, 2010).

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 SI.

In addition to this work, I have made theoretical calculations to study the stability of frontal currents to SI in the presence of frontogenetic or frontolytic strain. This calculation is relevant to the 2012 LatMix field campaign targeted for the North Wall of the Gulf Stream, where strong, confluent flow combined with large density contrasts and intense atmospheric forcing could give rise to a symmetrically unstable flow. The characteristic of this instability could be affected by the confluent strain field. The theoretical calculation is thus a first attempt to characterize this dynamics in anticipation of the observational study.

RESULTS

Winds blowing in the direction of geostrophic currents input energy into the ocean circulation. When those currents are baroclinic and surface intensified, 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 SI. High-resolution LES experiments show how this occurs (Fig. 1).

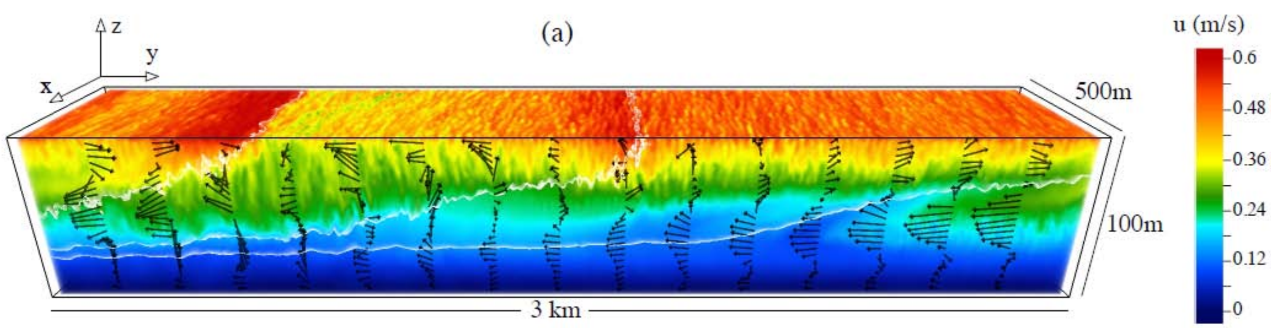

Fig. 1: A visualization of the buoyancy and velocity field in a large eddy simulation of wind-forced symmetric instability. Color shading denotes the along-front velocity, u. The velocity field in the y-z plane is shown using arrows, and three isopycnal surfaces are shown in white. The vertical coordinate and velocity vectors have been exaggerated by a factor of 5. Figure adapted from Thomas and Taylor (2010).

Forced SI driven by down. front winds extracts energy from the geostrophic flow at a rate given by the geostrophic shear production (GSP) which is proportional to the Ekman buoyancy flux (EBF), the dot product of the Ekman transport and the surface buoyancy gradient. The kinetic energy (KE) going into SI is converted to 3D turbulence through a secondary shear instability and ultimately dissipated at small scales. This is accomplished via a forward cascade of energy from large to small scales. Diagnostics of the spectral energy flux reveal that the flux is positive for all wavenumbers, quantifying the forward cascade associated with SI and its secondary instabilities (Fig. 2). The result implies that an effective way to dissipate the KE of balanced geostrophic flows is to make the potential vorticity negative and trigger SI.

The same winds that reduce the PV and drive SI and frontal dissipation also input KE to the circulation via the wind[7] work. This suggests that the rate of KE increase by wind forcing is reduced relative to the wind. work because of the KE sink associated with SI and small. scale shear instabilities. Indeed, the net result of this submesoscale sink of KE is to reduce the usable wind[7] work, i.e., the wind[7] induced rate of KE increase, by an amount that depends on the wind[7] stress and the change in geostrophic velocity across the mixed layer.

Observations from the Kuroshio support these predictions of enhanced dissipation at wind forced fronts. D'Asaro et al., “Enhanced mixing and energy dissipation at ocean fronts”, manuscript in preparation, 2010, describe observations of enhanced turbulence at a particularly sharp wind-forced front in the Kuroshio. The peak in the estimated dissipation that they observed coincided with the maximum in EBF, with the two quantities scaling with one another, and with negative PV, all indications that the elevated turbulence at the front was at least partially attributable to wind-forced SI.

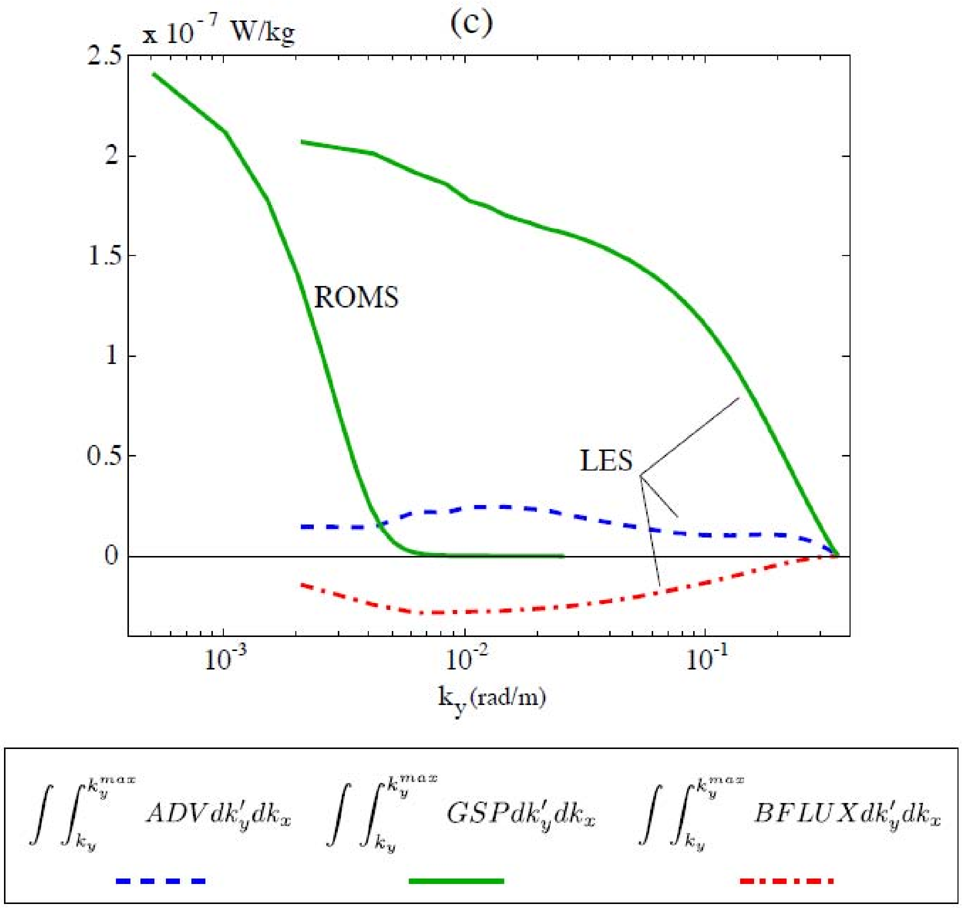

Fig. 2: The spectral energy flux (blue dashed) and cumulative integrals of the spectra of terms in the turbulent kinetic energy budget (TKE), i.e. the geostrophic shear production, GSP, (green) and the buoyancy flux (red). The GSP diagnosed from both the ROMS and LES experiments reveals that it is the dominant source term for the TKE.

These studies of SI have assumed that the fronts on which they form are not actively being strained by a confluent flow. In the real ocean however, fronts that are susceptible to SI are often accompanied by confluent strain, since the strain field leads to frontogenesis and the generation of the strong vertical shear on which SI derives its energy. It is an open question as to whether the addition of strain stabilizes or destabilizes flows that may be susceptible to SI. To address this question, I performed a linear fluctuation growth analysis for 2D perturbations added to a geostrophic flow with a spatially uniform vertical shear, horizontal density gradient, stratification, and confluence. In this simple system, the strain leads to an exponential increase in the horizontal density gradient with time, thus disrupting the thermal wind balance. An ageostrophic flow is induced to restore geostrophy, with a vertically sheared cross-front velocity (Fig. 3). The exponentially growing lateral density gradient results in an enhanced geostrophic shear, yet the flattening of isopycnals by the ageostrophic flow increases the stratification so that the Richardson number of the flow does not change with time.

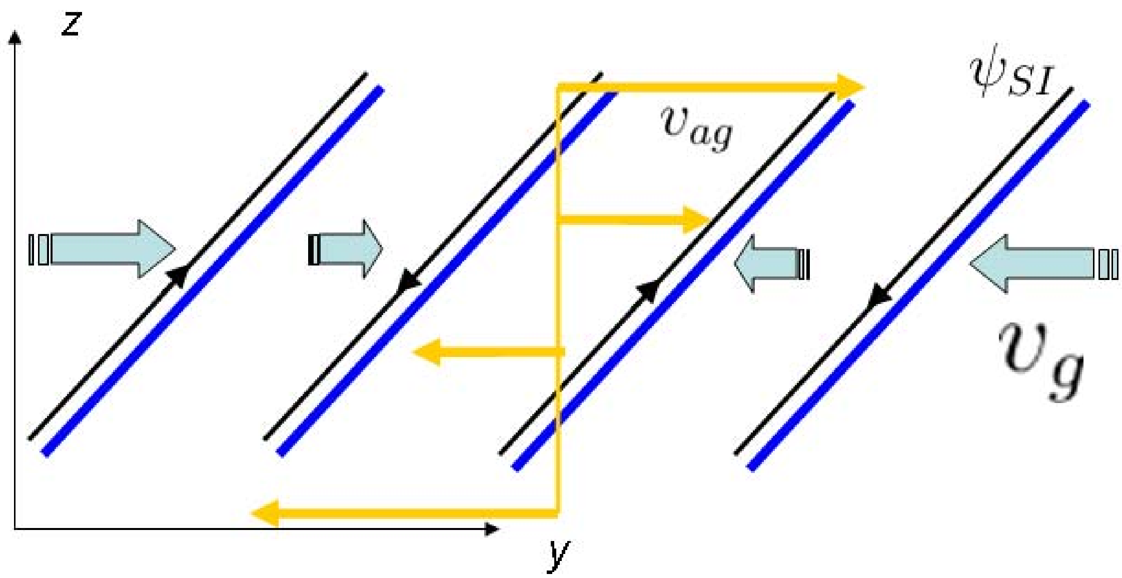

Fig. 3: Schematic showing the sense of the ageostrophic circulation, v_{ag}, (yellow arrows) that is induced by a confluent flow, v_g, (blue arrows), in the presence of a density field (blue contours) with a uniform horizontal density gradient. A 2D perturbation with overturning streamfunction, ψ_{SI}, (black streamlines) is introduced to this system and its growth is assessed.

A 2D perturbation, with a velocity field corresponding to the fastest growing SI mode in the unstrained system, was added to the flow field (e.g. Fig 3) and its growth was assessed for different values of the Richardson number and strain rate. This linear fluctuation growth analysis reveals that confluent strain reduces the growth of SI (Fig 4) and can even dampen out SI for strong enough strain and Richardson numbers near one. The implication being, for the LatMix field experiments in the strong, confluent strain characteristic of the flows near the North Wall of the Gulf Stream, we could observe a stabilization of SI if the Richardson number of the frontal flow is not too low.

IMPACT/APPLICATIONS

The results of these numerical experiments impact our understanding of the energetics of the ocean circulation. 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 world's oceans could reduce the amount of the wind-work available for accelerating the large-scale circulation by 5-15%. The implication being that this submesoscale phenomenon could play an integral role in setting the magnitude of the global circulation. Owing to its potential importance, John Taylor, Baylor Fox-Kemper (CIRES/CU), and I are developing a parameterization for the energy dissipation and tracer dispersal by SI. The parameterization will be implemented in coarse resolution numerical models.

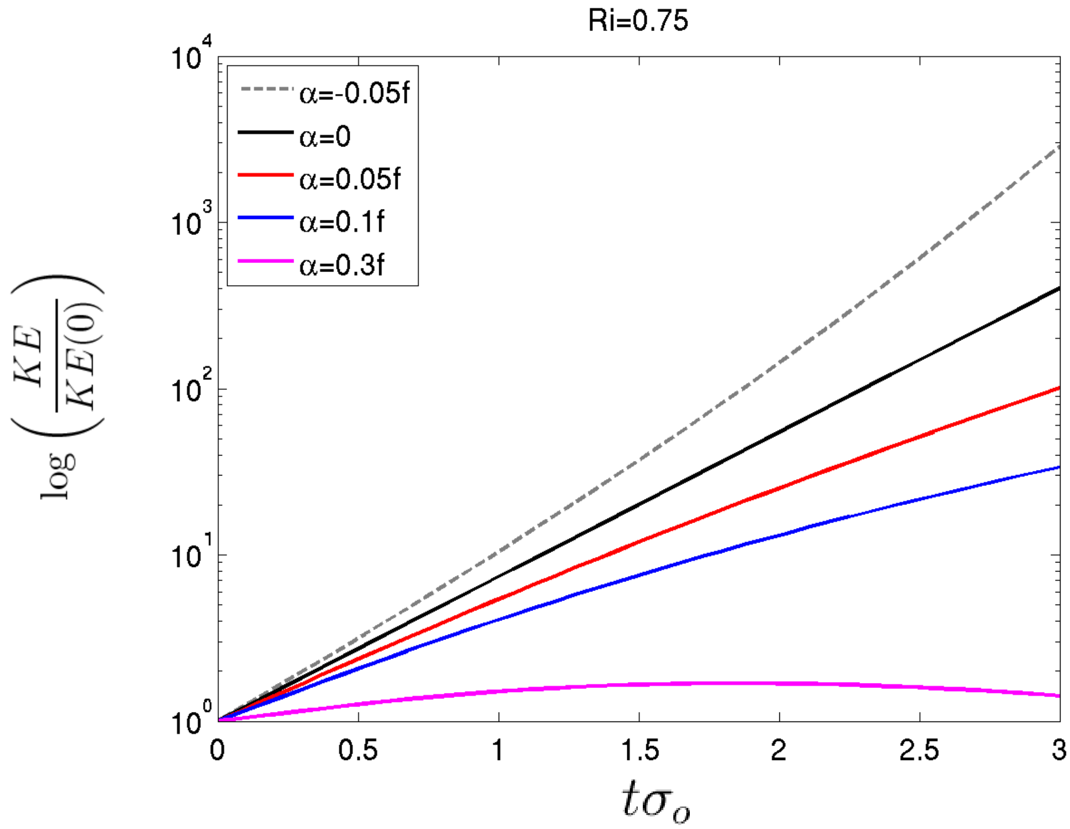

Fig. 4: Timeseries of the KE of the 2D perturbation (normalized by its initial value) added to the strained frontal zone shown in Fig. 3 with a Richardson number of 0.75. When the strain is confluent, i.e. the strain rate $\alpha > 0$, (red, blue, and magenta lines) the growth of the perturbation is reduced relative to the unstrained case (black line). The strain rate is expressed in terms of the Coriolis parameter f, and time is normalized by the growth rate of SI in the unstrained case.

REFERENCES

Thomas, L. N., and J. R. Taylor (2010), Reduction of the usable wind-work on the general circulation by forced symmetric instability, *Geophys. Res. Lett.*, **37**, L18606, doi:10.1029/2010GL044680.