Eddy-mixed layer interactions in the ocean

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Numerical models have become essential tools in the study and prediction of natural climate variability and anthropogenic climate change. However the skill of such models in simulating the observed climate variability is still severely limited by (1) numerical approximations in the discretization of the hydrodynamical equations and (2) imperfect parameterizations of the myriad of atmospheric and oceanic processes that happen at scales too small to be explicitly resolved by the model. In the 1960s, at the dawning of the age of numerical modeling, the accuracy of the numerical schemes was the real bottleneck. For example, early models of the ocean generated excessive mixing across density surfaces due to poor numerical discretization. Great strides have been made over the past four decades in overcoming these technical difficulties both through improvement of the numerical codes and through increase in computational power. Currently the major source of model error has become the imperfect or missing parameterization of unresolved processes.

In the U.S., a large fraction of the development and maintenance of IPCC-class models is carried by scientists working at specialized modeling centers. These centers have been successful in improving the numerical kernel of climate models. However the development of effective parameterizations is intellectually more challenging and cannot devolved to a few centers. It demands physical understanding of how the relevant process relate to the overall ocean and atmosphere dynamics, and a careful consideration of issues related to model resolution and numerical formulation. While the modeling centers have the expertise to deal with the latter, progress in basic understanding is typically the result of observations, theory, and idealized studies which involve the whole scientific community. Currently there is little coordination between research at the modeling centers and elsewhere. As a result, parameterizations in atmospheric and oceanic general circulation models do not reflect recent advances in our understanding of the corresponding processes. This is arguably the biggest bottleneck in improving high-end climate models.

Climate Process and Modeling Teams (CPTs) were created in 2003 by the U.S. Climate Variability and Predictability (CLIVAR) program to provide a thorough and efficient forum for improving model parameterizations. The idea of a CPT is to fund a small group of observationalists, theoreticians, small-scale modelers, and scientists at the modeling centers to work closely together to improve parameterizations of a particular process in one or more climate models. After a call for proposals, three pilot CPTs have been funded for a three year period: one CPT examining cloud-feedbacks in the atmosphere, and two smaller CPTs focused on ocean dynamics, one on eddy variability in the upper ocean and the other on

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gravity currents. The three pilot CPTs are currently being reviewed by the National Science Foundation to evaluate the effectiveness of the new framework. The goal of this brief paper is to summarize key results obtained by the CPTs so far and to provide a basis for discussion of the CPT approach within the scientific community.

1 The Climate Process Team on Eddy Mixed Layer Interactions

Ocean circulation models used in climate studies typically have mesh grids with a horizontal resolution close to one hundred kilometers, and a vertical resolution transitioning from ten meters at the surface to a few hundreds meters at depth. With such grids all the mesoscale variability (ocean cyclones and anticyclones) and microscale variability (turbulent mixing due to processes such as breaking internal waves and convection) are sub-grid scale and must be parameterized. Although more powerful computers may soon decrease the feasible grid scale to a marginal mesoscale eddy resolution of O(25) km, even finer grids of O(10) km or better are needed to adequately resolve the fluxes produced by mesoscale motions. Thus parameterization of both mesoscale and microscale processes is the only solution for the forseable future.

The CPT on eddy-mixed layer interactions was organized to improve the parameterization suite of sub-grid scale processes in the upper ocean. The decision to focus on the upper ocean was based on two main considerations. First, the Earth's climate is most sensitive to upper ocean dynamics where communication takes place between the atmosphere and the oceanic reservoir of heat, freshwater and carbon dioxide. Second, ocean mesoscale and microscale variability is strongly surface intensified and thus parameterizations have a larger impact on global climate close to the surface.

The upper ocean is typically characterized by a weakly stratified boundary layer (BL) overlying a more stratified thermocline. There is a rich literature on parameterizations of microscale turbulent mixing both in the BL and in the stratified interior. Less is know about mesoscale eddies and their parameterization is the primary focus of the CPT. The current paradigm for ocean eddy parameterization dates back to the work of Gent and McWilliams in the 90s, who realized that eddy fluxes are quasi-adiabatic in the ocean interior and should be represented as an eddy-induced velocity. The Gent-McWilliams (GM) scheme reduced climate drift in coupled ocean-atmosphere models and it has become a standard for climate studies. A major limitation of the GM scheme is that the adiabatic assumption is not valid in the BL where diabatic processes are strong. The common practice in ocean models today is to use ad hoc tapering functions to turn off the adiabatic eddy-induced velocity near the surface, without including any parameterization for the surface eddy fluxes. The tapering approach is at odds with the observational and theoretical evidence that eddy fluxes have a strong impact on the dynamics of the upper ocean. The CPT on eddy-mixed layer interactions used a combination of theory, observations, and process models to improve our understanding and parameterizations of the eddy processes in the BL. Due to space limitations, we cannot review all the research activities in the team. Instead we briefly list the ongoing research projects and we discuss how they contributed to the development of new parameterizations schemes.

1.1 Team activities

The CPT on eddy-mixed layer interactions is composed of 15 principal investigators working at 9 different institutions: three observationalists who lead numerous upper ocean studies (D. Rudnick, Scripps; K. Speer, Florida State University; R. Weller, WHOI), seven theoreticians with expertise in the study and parameterization of upper ocean processes (R. Ferrari, G. Flierl, and J. Marshall, MIT; J. McWilliams, UCLA; A. Tandon, Univeristy of Massachusetts at Dartmouth; L. Thomas, WHOI; G. Vallis, Princeton), and five scientists working at two modeling centers (G. Danabasoglu, P. Gent and W. Large, NCAR; R. Hallberg and S. Griffies, GFDL). Funding is used to partly support postdoctoral researchers at each participating institution. R. Ferrari has overall responsibility for the CPT program, coordinating the theory, modeling and observational activities, organizing investigator meetings, and promoting the CPT participation in relevant ongoing observational programs. With PIs distributed across the US, yearly workshops were extremely useful to coordinate research activities and spin off new collaborations. A web-site (http://cpt-emilie.org/) has been created to disseminate results and workshop activities. Finally, the CPT work will be presented in a special session at the Ocean Sciences Meeting in February 2006.

The focus of the CPT is on eddy variability in the upper ocean. There are two separate classes of eddies in the upper ocean: mesoscale eddies generated through baroclinic instability of the full water column with scales close to the internal deformation radius (≈ 50 km) and submesoscale eddies generated through ageostrophic baroclinic instabilities within the BL with scales close to the BL deformation radius (≈ 1 km). Neither class is currently parameterized in climate models. The team made progress toward the understanding and parameterization of both classes of eddies. Detailed results are reported in the CPT publication list at the end of the paper.

Mesoscale eddies control the subgrid lateral transport of tracers in the surface BL and the subgrid exchange of properties between the BL and the stratified interior. Both processes are important for the Earth's climate, especially on decadal timescales. Mesoscale eddies transport large amounts of heat in the Southern Ocean and in the Gulf Stream and Kuroshio Current regions. Eddy formation of mode waters strongly modulates air-sea fluxes in midlatitudes. As a result of the tapering of parameterizations in the surface BLs, these effects are missing in ocean models. A major challenge in the parameterization of submesoscale eddies is to identify and predict the transition region where fluxes develop a diabatic component. The observationalists in the team used a database of $> 70,000$ km of SeaSoar temperature and salinity data and ADCP measurements to estimate statistics of this transition layer. They found that the transition layer thickness is typically of the order of 10% the boundary layer depth and it is associated with enhanced shears and turbulence. These results, together with high analysis of high resolution numerical simulations carried out at MIT, Princeton, and UCLA provided the basis for the parameterization scheme described in the next section.

In the BLs eddies develop also at the submesoscale along density fronts generated by sudden changes in surface fluxes or by stirring of the large scale temperature and salinity gradients. The dynamics is quite simple. Once formed, these lateral fronts slump under the action of gravity with denser water flowing under lighter water. The slumping process is modified by rotation and generates eddies with scales close to the BL deformation radius of a few kilometers. Even though anecdotal evidence of submesoscale features pervades the upper ocean literature, there was no comprehensive study of their effect on BL dynamics. The CPT found that the slumping fronts efficiently restratify the BL and have a substantial impact on BL depth and sea-surface temperatures, two key dynamical variables for climate variability on timescales from days to decades and beyond. A parameterization for submesoscale eddies was developed using a hierarchy of high resolution numerical models at MIT and UCLA, and it is now being tested versus mooring observations. Preliminary results are discussed below.

The results obtained to date prove that CPTs are a viable framework to climate model improvement. Some of the research carried out by members of the CPT on eddy-mixed layer interactions would have happened regardless of the creation of a CPT. However the development of a full set of parameterizations for IPCC-class models would still be years away, because it relied on the close collaboration of scientists that were unlikely to interact outside the CPT. The team has been more than the sum of its members.

1.2 Parameterization of mesoscale eddies in the upper ocean

A new parameterization has been developed to represent the transition from adiabatic, isopycnally oriented mesoscale fluxes in the interior to diapycnal, along-boundary mesoscale fluxes near the boundaries (Ferrari and McWilliams, 2006). The parameterization stems from ideas first proposed by Treguier and Held at the end of the 90s and it is constructed as follow:

- In the ocean interior the closure scheme is essentially equivalent to the GM parameterization.
- In the turbulent BL, the parameterization is composed of two terms. An eddy induced velocity with zero shear, in the spirit of well-mixed BL models. And an along-boundary

down-gradient flux of density that represents the diabatic nature of mesoscale eddies in the BL.
- The interior and boundary layer parameterizations are matched by linearly interpolating through a transition layer, whose thickness depends on the slope of density surfaces below the BL base.

The new parameterization is supported by high resolution numerical simulations run by members of the CPT (Kuo et al., 2005) and has been implemented in the ocean component of the NCAR Community Climate System Model (CCSM3) and in the MITgcm Ocean Model at MIT. Here we report on results with a 3° resolution simulation with CCSM3. The most prominent and significant effects of the new scheme occur in the Southern Ocean where the mesoscale activity is expected to be the highest and in deep water formation regions of both hemispheres. The time-mean eddy-induced meridional overturning streamfunction distributions from the new scheme is compared with the original one in Fig. 1; the new scheme results in the elimination of the spurious near surface circulations whose strengths strongly depend on the ad-hoc tapering function of the original scheme. The result is a dramatic improvement in the vertical structure of the of heat flux as compared with eddy-resolving simulations (Fig. 1), inverse models (Lumpkin and Speer, 2005), and estimates from mooring observations in the Southern Ocean. The diapycnal eddy mixing in regions where the boundary layer is deep largely eliminates the warm biases of the control case at high latitudes. These results are very encouraging, and the CPT is now testing the robustness of the sensitivities observed and planning experiments to estimate the climate implications of these results.

1.3 Parameterization of submesoscale eddies in the upper ocean

Fox-Kemper and Ferrari (2006) formulated a parameterization for submesoscale restratification. The basic idea is that in the presence of a horizontal density gradient $\nabla_H \rho$, an overturning streamfunction develops which represents the slumping of the front,

$$\psi = c_e f^{-1} z(z+H)\hat{z} \times \nabla_H \bar{b}, \qquad -H \le z \le 0, \tag{1.1}$$

where H is the BL depth, f the inertial frequency, and c_e an efficiency factor of order one. The parameterization has been tested versus idealized simulations exploring the parameter regime relevant for the ocean surface BL (Fig. 2a). This parameterization is readily applied to climate models, and preliminary tests have been run at GFDL with the Hallberg Isopycnal Model (HIM) in coupled ocean-atmospehre simulations. The main impact on model output is a strong reduction of the mixed layer depth (of order 30% in midlatitudes) after mixing events (*e.g.,* after a winter convective event) leading to a noticeable decrease in the time-mean mixed layer depth when compared to a control simulation (Fig. 2b). The dominant signal is accentuated in regions of strong gradients (e.g., western boundary current

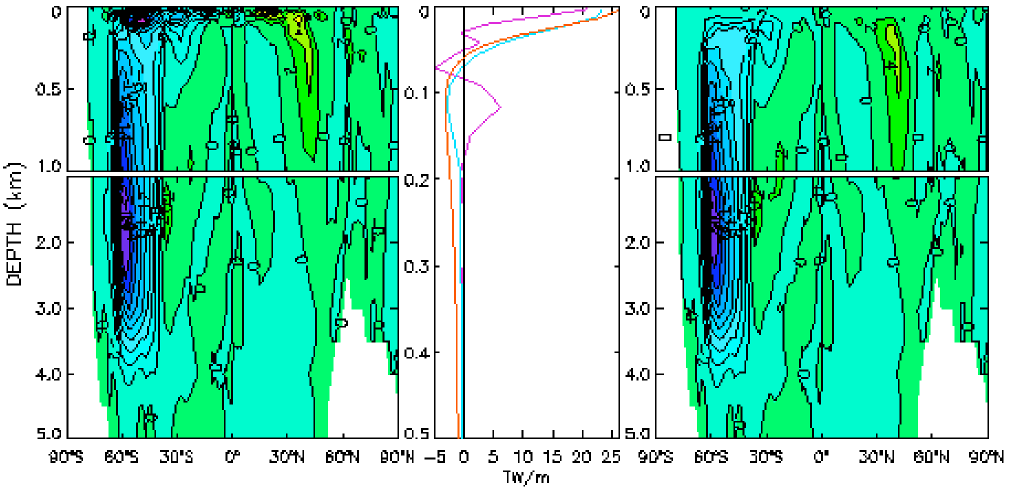

Fig. 1. Time-mean eddy-induced meridional overturning streamfunction produced with CCSM3 (NCAR). Output from a control simulation with the GM eddy parameterizations (left panel) and from a run using the new parameterization developed by the CPT (right panel). Contour interval is 2 Sv. The positive and negative values indicate clockwise and counter-clockwise circulations. The center panel shows the zonally averaged heat flux across 47°S in the upper 1000 m from the control run using the GM parameterization (purple line), the run using the new parameterization (cyan line) and a 1/8° global eddy resolving simulation run with the MITgcm (red line).

extensions) and deep convection (e.g., the Nordic Seas). The CPT is now pursuing a comparison of these results versus available climatologies of ML depth. The next step will be to test the climate sensitivity to the reduction in ML depth.

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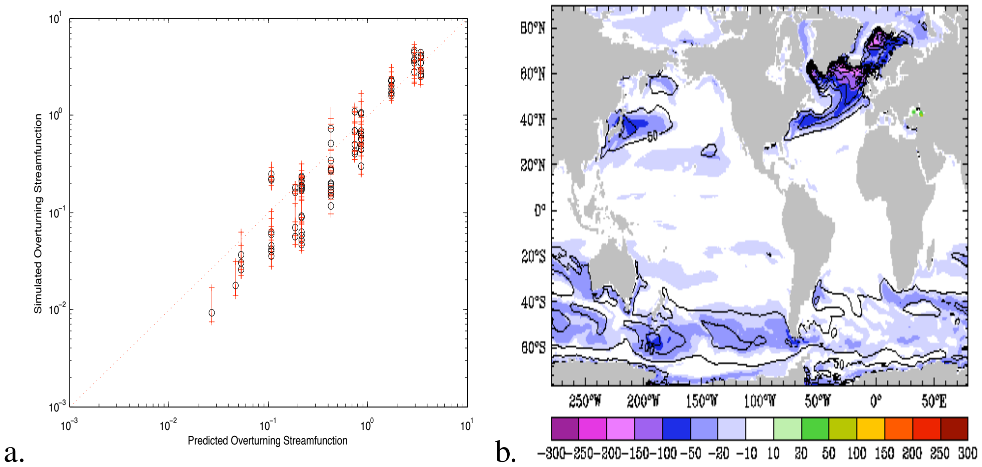

Fig. 2. a) Parameterized versus resolved submesoscale eddy overturning streamfunction generated by simulations of a slumping horizontal front in a turbulent boundary layer subject to diurnal surface fluxes. The simulations are run with the MIT general circulation model and differ for front strength and width, vertical stratification and turbulent boundary layer scheme (see movies at http://cpt-emilie.org/). b) 5-year mean surface mixed layer depth changes after 10 years between control run and a run with the parameterization for submesoscale restratification. Simulations were run at GFDL with the HIM model at 1° resolution. The submeso-scheme substantially reduces the boundary layer depth at high latitudes in winter.

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