

## Introduction

The goal of the Gravity Current Entrainment Climate Process Team is to improve the representation of dense gravity currents or overflows in ocean-climate models. Dense waters formed in marginal seas or on coastal shelves enter the open ocean by flowing through narrow channels and down the continental slope, entraining and mixing with overlying water. Present climate models have insufficient resolution to capture these mixing processes or even in some cases the small scales of the important topographic channels, and therefore cannot correctly simulate the dense water masses which result, some of which (e.g. North Atlantic Deep Water, Antarctic Bottom Water) play very important roles in the large-scale ocean circulation.

The Gravity Current Entrainment Climate Process Team was established by U.S. CLIVAR, and funded by NSF and NOAA, to foster the collaboration between climate model developers and those conducting observational, numerical and laboratory process studies in order to facilitate the timely development of improved model representation of overflows.

## The Structure of the Climate Process Team

Our climate process team consists of groups from two of the modeling centers, NCAR and GFDL, observationalists at WHOI, LDEO and Miami, process modelers from WHOI, Princeton and Miami, and additional model developers at Miami. The bulk of our funding has gone toward fulltime postdocs at WHOI and Miami, a halftime postdoc at GFDL and a halftime researcher at NCAR, both of whom are shared with the other ocean CPT. Annual workshops have been the principal mechanism for establishing our collaboration, with important followup at other conferences and meetings and through email and our webpage <http://www.cpt-gce.org>. The workshops have also been an important route for interacting with other members of the community, and have included presentations from many other observationalists and process modelers. The project is now partway through its third year, and we have applied to NSF for 2 more years of funding.

## Results

Our results can be separated into 2 broad classes, defined by the model vertical coordinate. Whereas height-coordinate models at coarse climate model resolution have great difficulty moving dense fluid down a slope without introducing excessive mixing, isopycnal-coordinate models have no diapycnal mixing unless explicitly parameterized. The issues therefore become: (a) For z-coordinate models, how do we move dense fluid down the slope while limiting diapycnal mixing? (b) For isopycnal-coordinate models, what is the correct parameterization of mixing? An important step in determining the areas to focus on and evaluating new model developments has been a careful intercomparison of current model capabilities for idealized overflows (Legg, Hallberg and Garton, 2006; Anderson, 2005; Ezer and Mellor, 2004; Ezer, 2005) and comparison of regional model simulations with observations (Riemenschneider and Legg, 2006; Xu et al, 2006; Chang et al, 2006; Ezer, 2006). We continue to extend our understanding of the mixing in overflows through nonhydrostatic simulations of the effects of complex bottom topography and ambient stratification on overflow entrainment (Ozgokmen et al, 2004b, 2006) and review of observations ([http://www.cpt-gce.org/Table\\_of\\_observations.htm](http://www.cpt-gce.org/Table_of_observations.htm)).

## The Marginal Sea Boundary Condition

For coarse resolution models an attractive approach is to parameterize all the sub-grid-scale physics and topography involved in an overflow. A promising basis for such a parameterization is the Marginal Sea Boundary Condition, developed by Price and Yang (1998). While they included it in idealized ocean models, through the CPT the NCAR team has incorporated the MSBC into a full ocean climate model (the CCSM) for the first time (Wu et al, 2006). In the first stage of implementation, it completely determines the transports, tracer properties and depths of the inflows and outflows associated with exchanges between the modeled Mediterranean Sea and North Atlantic, where a realistic Mediterranean salt tongue is generated (figure 1). The next stage, a Nordic overflow implementation, is underway. The goal is to include all the climatically important overflows. This endeavor is being assisted by (i) a comparison table of observations of overflows produced by observational members of our team, which gives some of the input parameters needed for the MSBC, and is available on the CPT webpage; (ii) high resolution regional simulations, especially of the Nordic overflows, produced by Ulrike Riemenschneider which provide guidance on aspects of the flow such as where entrainment occurs; (iii) improvements to the MSBC being pursued by Price and Yang, to make it more suitable for time-varying flows.

## Mixing Parameterizations in layered ocean models

In models where the vertical coordinate is based on density, explicit parameterizations of mixing are needed to generate the observed modifications to the dense water masses. At the onset of the Climate Process team, there were two parameterizations of interior mixing available in such models: a parameterization based on the entrainment formula of Ellison and Turner (1959), implemented in layered models by Hallberg (2000); and a diffusivity based on the Pacanowski-Philander parameterization, employed as the interior mixing parameterization in the KPP vertical mixing scheme of Large et al (1994).

The CPT has led to the following results and improvements for mixing parameterizations in isopycnal and hybrid coordinate models:

i.) The Ellison-Turner type parameterization, with nondimensional constants originally determined from laboratory measurements of the entire dense layer, has been calibrated by Miami researchers for implementation in the Hybrid Coordinate Ocean Model (HYCOM), by comparison with idealized nonhydrostatic overflow simulations by Ozgokmen et al. (2004a). Good agreement is found with observations when used in regional HYCOM simulations of real overflows such as the Red Sea and Mediterranean provided resolution is sufficient to capture the narrow channels (Figure 2) (Xu et al, 2006; Chang et al, 2006).

ii.) A parameterization of mixing due to bottom friction has been developed by Robert Hallberg, following comparison between nonhydrostatic MITgcm simulations and HIM isopycnal model simulations (Legg et al, 2006), stimulated by discussion with Hartmut Peters concerning the different mixing in bottom and interfacial layers of the Red Sea overflow. This parameterization eliminates spurious splitting of the dense plume, and greatly improves simulations of the Mediterranean overflow when implemented in the Hallberg Isopycnal model, combined with the Hallberg (2000) implementation of the Ellison and Turner scheme.

iii.) To the extent that mixing in overflows is driven by the shear, one might expect existing parameterizations of shear-driven mixing to be suitable for representing mixing in overflows. However, Miami researchers have shown that one such parameterization, the KPP interior mixing

component, gives too little mixing for overflows (Chang et al., 2005), having been originally calibrated for the equatorial undercurrent. Similarly Ellison-Turner type parameterizations give too much mixing in the equatorial undercurrent when calibrated for overflows. A new parameterization of shear-driven mixing is clearly needed for use in global models. Laura Jackson and Robert Hallberg are developing such a parameterization, with an eddy diffusivity  $\kappa$  which satisfies

$$\frac{\partial^2 \kappa}{\partial z^2} - \frac{\kappa}{L_B^2} = -2SF(Ri)$$

where  $S$  is the vertical shear of the resolved horizontal velocity, and  $L_B = Q^{1/2} / N$  is the buoyancy length scale (the scale of the overturns) with  $Q$  the turbulent kinetic energy (TKE) found from an energy budget and  $F(Ri)$  is a function of the shear Richardson number  $Ri$ . The parameterization is being calibrated against direct numerical simulations and LES from GFDL and Miami, with initial results looking promising.

## Ongoing and future work

CPT Researchers are continuing to implement the new and improved parameterization schemes in global climate models at NCAR, GFDL and Miami, and examine the sensitivity of ocean-only and coupled climate simulations to the representation of overflows. If the CPT is extended, a major emphasis will be on the treatment of straits narrower than the climate model resolution, with possible methods of dealing with this problem including high-resolution regional simulations for each overflow, 2-way nested models, or partially open barrier algorithms.

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## Figure Captions

Figure 1: Comparison between observed and modeled salinities in the vicinity of the Mediterranean outflow plume, at 1100m depth. Top left: World Ocean Atlas 1998 climatology; top right: ocean-

only model results without Marginal Sea Boundary Condition; bottom left: ocean-only model results including the Marginal Sea Boundary Condition at Gibraltar; bottom right: Coupled model results including the Marginal Sea Boundary Condition at Gibraltar. Model results are averaged over 1 year, after 250 years of integration. (Wanli Wu, William Large and Gokhan Danabasoglu, NCAR).

Figure 2: Comparison of the salinity distribution modeled by HYCOM with that from REDSOX-1 observations (Peters et al., 2005) along the "Northern channel", which is a narrow (3-5km wide) channel transporting approximately half of the Red Sea overflow water after the overflow bifurcates shortly downstream of the Bab-el-Mandep strait. The model has a horizontal resolution of 1 km and 12 vertical layers, and uses the version of the Turner (1986), Hallberg (2000) parameterization tuned by Xu et al. (2006) (Yeon Chang, Tamay Ozgokmen, Hartmut Peters and Xiaobao Xu, U. Miami).