Improving oceanic overflow representation in climate models: the Gravity Current Entrainment Climate Process Team

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Capsule Summary

Collaboration between observationalists, theoreticians, and process and climate modelers leads to new understanding of oceanic overflows, and hence to improved representation in ocean climate models.

Abstract

The Gravity Current Climate Process team was established by US CLIVAR, and funded by NSF and NOAA, to improve the representation of oceanic overflows in climate models. Oceanic overflows are deep currents of dense water originating in semi-enclosed basins such as the Greenland-Iceland-Norwegian sea, or on continental shelves such as the Antarctic shelf. After negotiating narrow straits in some cases, the dense waters flow down the continental slope, entraining and mixing with ambient waters along the way. Overflows are the source of most of the abyssal waters, and thus they play an important role in the large-scale ocean circulation, for example by forming the sinking branch of the thermohaline circulation. Yet, mixing processes in the overflows are poorly represented in current climate models with a resulting impact on the accuracy and credibility of climate model predictions. This climate process team, now nearing its completion, brings together climate model developers with those conducting observational, numerical and laboratory process studies of overflows, with the aim of accelerating the transfer of new understanding into improved climate model parameterizations. This pilot program is intended to lay the ground work for a new framework for climate research, involving close connections between process studies and climate model development. Here we describe the organization of our Climate Process Team, highlight the successes and lessons learned during our collaboration, and summarize the principal model developments achieved by the initiative.

The "Gravity Current Entrainment Climate Process Team" was established by US CLIVAR (Climate Variability and Predictability program) to improve the representation of oceanic overflows in climate models by encouraging translation of new understanding from observations and process models into new parameterizations. Here we describe the organization of this new framework for climate research, and highlight the successes achieved to date during our collaboration.

Modern climate predictions and projections of future climate change are increasingly made with global coupled ocean-atmosphere models (IPCC, 2007). The credibility of these models is limited by their ability to represent climatologically important processes occurring on scales smaller than the climate model grid scale, currently typically 100 kilometers. One such small scale phenomenon having global importance are the overflows, shown in figure 1. These overflows, or dense gravity currents, result when dense water formed behind confining topographic barriers or on a continental shelf, escapes into the deep ocean over a sloped sea floor. Important examples of the former are the overflows of dense water from the subpolar seas of the northern North Atlantic (Girton and Sanford, 2003; Mauritzen et al., 2005) and from the subtropical Mediterranean (Price et al., 1993) and Red Seas (Peters et al., 2005). The continental margin prime example occurs around Antarctica, notably in the Weddell (Foldvik et al., 2004) and Ross Seas(Gordon et al., 2004). Since much of the deep ocean water masses are derived from the Nordic and Antarctic overflows, the tracer properties of these overflows set the climate of the deep ocean. Overflows are an essential part of the cold branch of the overturning circulation; hence their density and transport likely influence the thermohaline circulation.

As dense water passes from its formation site into the open ocean through an overflow, it undergoes mixing with overlying water, which determines the eventual properties and volume of the resultant deep water mass. Credible climate projections require that these overflow processes be represented in ways that reproduce both the modern overflow-derived plumes and any known changes in these plumes in response to changes in the ambient ocean state. However, because these processes occur below the grid-scale of our highest resolution global ocean models, realistic representation of overflows poses a considerable challenge for numerical simulation.

Overflows not only influence the deeper watermasses, but also affect the surface layer temperature and oceanic heat flux, through dynamical coupling with the overlying upper ocean. Similarly, localized overflow processes, such as a change in thickness of the overflow layer, can influence the basin-wide circulation by affecting the potential vorticity budget (Yang and Price, 2007) and dissipative processes in the overflow also affect the inter-basin transport. The entrainment and eddying processes associated with overflows (Kida et al., 2007) can lead to upper ocean responses in the form of cross-basin beta-plumes. Without proper influence of overflows on these processes, model simulations of thermohaline changes, for example those induced by large freshwater fluxes in the North Atlantic (Stouffer et al., 2006) may not be reliable. One goal of our collaboration is to assess the climate impacts of new representations of overflows implemented in ocean models.

The climate process team: a bridge between field observations, process modeling and climate model development

Field, laboratory and theoretical process studies of overflows have increased our understanding of overflow processes. However, to translate this detailed understanding into a form that can serve to improve climate modeling requires a close collaboration with climate model developers. The climate process team (CPT) framework is an attempt to bridge the communication gap between those researchers studying a particular process, and the climate model developers. In this pilot phase, the overall CPT effort comprised one atmospheric CPT, and two ocean mixing CPTs, of which ours is one. Our particular CPT, focused on improving the representation of overflows, is composed of observationalists involved in recent field programs (Price, Gordon, Peters); process study modelers carrying out idealized simulations (Legg, Yang, Özgökmen, Ezer); and developers of general circulation models (Hallberg, Griffies, Large, Danabasoglu, Chassignet). The bulk of the 5 year funding from the National Science Foundation (NSF) and National Oceanic and Atmospheric Administration (NOAA), ending in 2008, has gone toward full-time postdocs at Woods Hole Oceanographic Institution and Miami, and a postdoc at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and a researcher at the National Center for Atmospheric Research (NCAR) who are both shared with the other ocean CPT, as well as annual workshops which have benefited from additional researchers from outside this core group.

A prerequisite of any new parameterization is that it should accurately reproduce the most important features of the observations. Hence an important task of the CPT has been to consolidate the observations of gravity currents into a comparative table. The overflows shown here are those which have been reasonably well sampled and which produce important water masses: the Denmark Strait and Faroe Bank Channel outflows from the Greenland/Iceland/Norwegian Sea, the Mediterranean outflow, the Red Sea outflow and the Antarctic gravity currents in the Weddell and Ross Seas. This comparative analysis of the main gravity currents allows us to identify common characteristic features, those that must be properly incorporated into model simulations. The Table of Observations (shown in abbreviated form here as Table 1) gives a series of metrics which define the gravity currents: the temperature, salinity, density field at the source and final product of the descending waters; spatial scales of the structures, and associated speeds and time scale of the events, and presents characteristic values of these metrics so that the various gravity currents may be easily compared. We find that there are many similarities, which bodes well for parameterization of gravity currents in the global ocean models.

Several different models are in use by the team members, as shown in Table 2. These include models whose primary purpose is high resolution nonhydrostatic simulation; regional or idealized calculations; global climate simulations or combinations of the three. Simulation of overflows is especially sensitive to the vertical coordinate scheme, and the CPT has utilized each of the three principal types employed in by ocean models today - height or pressure coordinates, terrain-following coordinates, and density coordinates. Each scheme has specific short comings and benefits with regards to the representation of overflows. By including all three types we can cross-compare results, find solutions most appropriate to each model type, and find solutions which can benefit multiple model types. Our strategy is to utilize process models to develop parameterizations and then to test and refine these parameterizations in the setting of an Ocean General Circulation Model (OGCM), with continual reference back to observations.

Overflow process simulations have been conducted in idealized domains, including an overflow scenario developed as part of the earlier Dynamics of Overflow Mixing and Entrainment (DOME) collaboration. These have served to demonstrate the important physical processes operating in overflows, the sensitivity of overflow features such as eddies and mixing to external parameters, and the sensitivity of model simulations of these features to model parameters such as resolution, vertical coordinate and subgridscale parameterizations. High resolution idealized calculations also serve as benchmarks against which to test parameterizations in coarse resolution simulations. Some of the process studies carried out as part of the CPT are documented in Anderson (2004), Ezer and Mellor (2004), Ezer (2005), Ezer (2006), Legg et al. (2006), Legg et al. (2007), Özgökmen et al. (2004b), Özgökmen et al. (2004a), Özgökmen et al. (2006), and Özgökmen and Fischer (2008).

Physical processes in overflows.

Overflows include several different physical processes, all occurring below the resolution of most climate models. First, the dense water must often flow through a narrow channel or over a sill, where hydraulic processes may control the transport and extent of local mixing and entrainment. Next the dense water descends the continental slope, accelerating en route due to its density anomaly, often with augmentation by thermobaric processes especially in cold overflows. Frictional processes at the sea-bed influence the flow field and mixing. The velocity difference between the accelerating dense water and the overlying water leads to shear instability at the upper interface of the overflow, resulting in entrainment of overlying water. This entrainment dilutes the overflow, and increases its transport. In many oceanic overflows, planetary rotation plays a significant role in steering dense water along topographic contours. The only way that the dense water can move downslope is by breaking this geostrophic constraint, i.e. either in the Ekman layer or through baroclinic instability. Eventually the dense fluid may find a neutral buoyancy level, at which point it can detach from the slope into the ocean interior, assisted by the mesoscale eddies resulting from baroclinic instability. If an ocean model is to produce deep or intermediate water with the correct tracer properties, and at the correct rate and in the correct place, it must correctly account for all of these processes (Figure 2). Different model types have to deal with different issues when modeling overflows: for example height-coordinate models at very coarse resolutions have difficulty moving fluid down the slope without introducing excessive spurious mixing; isopycnal models on the other hand need to explicitly parameterize mixing or no entrainment will occur. All coarse resolution models must choose how to deal with the sub-grid-scale processes and topography that govern overflows. The CPT framework has fostered two contrasting approaches that have been explored simultaneously. The first, known as the Marginal Sea Boundary Condition (MSBC) (Price and Yang, 1998), removes overflow regions from the OGCM, and uses inflow/outflow side boundary conditions to represent the net effects of the overflow both upstream and downstream. These boundary conditions are the outputs of an overflow parameterization, which attempts to represent all the important small-scale physics, such as hydraulic control, channel width, entrainment and shelf slope, as well as heat, salt and mass conservation. In general, the inputs are the evolving ocean state (temperature, salinity and density) both upstream and downstream of the overflow, as in the NCAR Mediterranean overflow implementation (Wu et al., 2007). The MSBC implementation in HYCOM, which does not have a prognostic representation of the Mediterranean, instead diagnoses the Mediterranean water properties from the climatological fluxes over the Mediterranean basin.

The alternative approach attempts to parameterize the important overflow physics in terms of the OGCM's resolved current and density structure. Eventually, there could also be some local grid refinement to resolve the topography as well, but in most current implementations narrow straits are artificially widened. Here, to illustrate further the workings of the CPT, and to show how results are being incorporated into climate models, we will focus on one process, the entrainment due to shear-driven mixing.

Prior to the start of the CPT, there were two parameterizations of shear-driven mixing in common use in climate models. One, the Turner-Ellison parameterization (TE), has been implemented in isopycnal and hybrid-coordinate models (e.g. GOLD, MICOM, HYCOM). TE assumes that the net entrainment into a region where the shear Richardson number (Ri) drops below some critical value is proportional to the velocity shear integrated across this region times a function of the shear Ri (Hallberg, 2000), and is derived from the bulk entrainment parameterization of Turner (1986) based on earlier laboratory experiments (Ellison and Turner, 1959). TE gives qualitatively reasonable depictions of gravity current entrainment in some circumstances (Papadakis et al., 2003;

Legg et al., 2006), but when this parameterization has been applied globally, including in the upper ocean, it leads to excessive shear-driven entrainment in the Pacific Equatorial Undercurrent.

In the second category of parameterization, which includes the Pacanowski and Philander (1981) parameterization and the component of KPP (the K-Profile Parameterization, Large et al. (1994)) applied in the stratified ocean interior, the shear-driven diffusivity is equal to a dimensional constant multiplied by a nondimensional function of shear Ri. These parameterizations were originally developed and calibrated for the shear-driven mixing in the equatorial Pacific, and there is apriori no reason to assume that they would be appropriate for overflows.

A first step undertaken by the CPT was to evaluate the existing parameterizations in the context of overflows. Idealized simulations of dense water flowing down a constant slope, using HYCOM employing KPP and the Hallberg implementation of TE were compared and calibrated against 3D nonhydrostatic large eddy simulations (LES) of dense gravity currents (using the Nek5000 model) from Özgökmen et al. (2004b). Whereas TE could be tuned to give good results compared to the LES, KPP has a pre-set upper limit to the diffusivity, and therefore gives a less physical response (Chang et al., 2005). The best approximation that uses the same formalism as TE, found from a comprehensive study employing several LES calculations, is a linear parameterization known as TPX: $E = w_E/\Delta U = 0.20(1 - Ri/0.25)$ for $Ri < 0.25$ and $E = 0$ for $Ri > 0.25$ (Xu et al., 2006). (E is the entrainment coefficient, w_E is the entrainment velocity, ΔU is the horizontal velocity difference between overflow and ambient water). TPX has now been implemented in HYCOM. Figures 3 and 4 show the comparison between the Nek5000 simulations and HYCOM simulations with the new parameterization.

In parallel with these developments, a new parameterization of mixing driven by frictional processes at the bottom boundary, the Hallberg Bottom Boundary Layer model (HBBL), has been developed. HBBL was inspired by the observed structure of the Red-sea outflow plume, in which there are two distinct and well-defined regions of vigorous turbulent mixing (Peters et al., 2005); a stratified and sheared interfacial layer, and a nearly homogenous turbulent bottom boundary layer. The former is well captured by TE, but when this is the only mixing parameterization in use, near-bottom viscous suppression of the shear keeps the bottommost water well stratified, and a sub-Ekman-layer thick sheet of overflow water flows into the abyss undiluted. Legg et al. (2006) find that the plume structure obtained with nonhydrostatic simulations can be reproduced nicely by an isopycnal model employing HBBL where a specified fraction (here 20% - a typical efficiency for mechanically driven diapycnal mixing) of the energy extracted by the model's bottom drag is used to homogenize the near bottom density.

Another track in parameterization development has been motivated by the observation that when TE-like parameterizations, tuned for overflows, are implemented globally, excessive mixing results in the Pacific equatorial undercurrent where shear-driven mixing is also an important process. In a global model it is not desirable to have to tune a shear-mixing parameterization individually for each location where it is applied. Motivated by this Jackson et al. (2007) have developed the Jackson-Hallberg Scheme (JHS), a parameterization scheme appropriate for representing shear-driven mixing in overflows and equatorial jets in climate models. In JHS the mixing is dependent on the shear forcing and a length scale which is a combination of the width of the low Ri region and the buoyancy length scale over which turbulence decays. It also allows a vertical transport of turbulence, from regions with a low Ri to the surrounding areas over a buoyancy length scale, which comparisons with high resolution simulations reveal to be an important physical process missing from parameterizations based on the local Ri (figure 5). JHS has been implemented into GOLD and is being tested in regional and global simulations. Early results show that when JHS is implemented globally with no additional tuning, credible results are produced both in the Equatorial Pacific Undercurrent and in the North Atlantic overflows.

In summary, the CPT collaboration has led to the development of new and improved parameterizations of shear-driven mixing in overflows, which when implemented in isopycnal ocean models have made these models viable components of a coupled climate modeling system.

Improved climate models: a case study of the Mediterranean Outflow

To demonstrate the multi-pronged approach we have taken to improving climate model representation of overflows, we focus on the Mediterranean outflow. It is an attractive overflow for parameterization development and evaluation because the depth at which the overflow water equilibrates is highly sensitive to the amount of entrainment; there are no major topographic features beyond the Strait of Gibraltar; it is perhaps the best-studied overflow, with good data sets available for comparison with model results.

The Mediterranean overflow makes a dense, bottom-trapped gravity current that flows down the continental shelf and slope into the Gulf of Cadiz and then into the mid-depths of the eastern subtropical North Atlantic. At the Strait of Gibraltar, there is a two-layer baroclinic exchange flow with an outflow of saline Mediterranean water, S $\approx$ 38.4, and an inflow of fresher North Atlantic water, S $\approx$ 36.2, (Price et al., 1993; Baringer and Price, 1997). The volume transport in either layer has been reported in the range $0.7 - 1.0 Sv$, (Bryden et al., 1994; Candela, 2001) and salinity transport in the outflowing layer (salinity anomaly times volume transport) is 1.5 to 2.2 $\times 10^6 m^3$ s^{-1}.

As the Mediterranean overflow descends the continental shelf and slope of the Gulf of Cadiz it mixes intensely with the overlying North Atlantic water. Most of the mixing, and hence most of the change in Mediterranean overflow salinity and temperature, occurs within 100 km of the St. of Gibraltar, near the region where the overflow descends the shelf-slope break (6.1 W to 6.6 W). In this 50 km segment of the path, the transport-weighted average of the salinity decreases from 38.0 to 36.5. An interesting feature of the Mediterrranean overflow is the development of two distinct cores by about 100 to 150 km downstream, after the majority of the mixing has taken place. The deeper offshore core has a central density of about $\sigma_\theta = 27.8$ kg m^{-3} while the shallower, onshore core has a density of $\sigma_\theta = 27.5$ kg m^{-3}. This variation, not present within the Strait of Gibraltar, results from differential entrainment (Baringer and Price, 1997; Xu et al., 2007).

The properties of the Mediterranean overflow water (MOW) in the Strait of Gibraltar and in the open North Atlantic have been undergoing a secular change over the past 50 years. The densest MOW outflowing through the Strait of Gibraltar has warmed by 0.3 degrees C and has simultaneously become saltier by about 0.06, compared with conditions only 20 years before. There has been little net change in density (Millot et al., 2006). These changes may result from the diversion of river inflow to the Mediterranean Sea (Rohling and Bryden, 1992) or a change in the regional origin of the overflow water (Millot et al., 2006). The equilibrated, mixed MOW found in the open North Atlantic thermocline has also become warmer and saltier over the past 40 years, by about 0.1 degrees per decade and 0.03 PSU per decade (Potter and Lozier, 2004). Whether and how these changes in T/S properties are related is something we hope to understand by learning some of the possible consequences of changing overflow properties.

Key features of the observations to be compared with numerical models are therefore the salinity difference and transport at the straits and downstream, the location and magnitude of entrainment, the emergence of a double core structure and the changes in overflow waters which result from changes in source waters.

Regional simulation of the Mediterranean overflow, using HYCOM at high-resolution (0.08° horizontal grid spacing, 28 coordinate layers in the vertical) with the TPX entrainment parameterization described above allows this parameterization to be evaluated by comparison with field data from the Gulf of Cádiz Expedition (Price et al., 1993). The high horizontal resolution allows for a reasonably realistic topography and the HYCOM regional model is able to reproduce quite well the major water property changes within about 150 km west of the Strait of Gibraltar via entrainment as well as the transition of the outflow plume from a bottom-trapped gravity current to a wall-bounded undercurrent at about 8°W (figure 6).

The solution is sensitive to the choices made for horizontal and vertical resolution: when the resolution is made coarser, the simulated currents (and associated vertical shear) are less vigorous and there is consequently less entrainment (Xu et al., 2007), which will impact coarse resolution climate simulations with this same model.

As already mentioned earlier, an alternative approach to explicitly simulating the outflow in a high resolution model, as done above, is to use an outflow model such as the Price and Yang (1998) Marginal Sea Boundary Condition, or MSBC. Since both the explicit simulations with HYCOM (0.08° horizontal grid spacing) (Xu et al., 2007) and stand-alone calculations with MSBC (Price and Yang, 1998) are able to reproduce the current state of the Mediterranean overflow reasonably well under present climate conditions, it is therefore useful to compare the sensitivity of MOW product water to changing conditions in both explicit HYCOM simulations and in MSBC. Our presumption is that the HYCOM/TPX regional model gives the more reliable result, since it is less idealized and constrained than the MSBC. Hence if the MSBC in stand-alone form is found to agree with the HYCOM simulations, then it would appear to be a viable candidate for use in a coarse resolution climate model that would not otherwise represent the Mediterranean outflow.

To this end, two sets of experiments, employing the regional HYCOM model and the MSBC respectively, were designed to investigate the sensitivity of the outflow product water to imposed variations of the outflow source water and ambient oceanic water (North Atlantic Central water), which might result from variations in air-sea fluxes in the Mediterranean basin and subtropic North Atlantic respectively. As shown in 7, these two experiments give similar predictions for the sensitivity of MOW product water in terms of volume transport, T/S properties, and equilibrium depth. An important result common to both models is that the salinity of the product waters are remarkably insensitive to density change in the outflow source water, and yet quite sensitive to a similar change in the oceanic water. The volume transport of the product water is equally sensitive to the density change in either the source water or the oceanic water. Therefore due to the dilution of MOW source water by entrainment, a (small) increase of the deep water salinity in the Mediterranean basin will be expected to result in a somewhat greater volume of MOW product water having only a very slightly greater salinity than is found at present (Xu et al., 2007).

Having shown that the MSBC in stand-alone form is able to reproduce the results of an explicit regional simulation of the Mediterranean outflow under changing climate conditions, we are now justified in implementing this overflow representation into a fully coupled climate model. A modified version of the MSBC (referred to as the parameterized Mediterranean outflow, PMO, below) was implemented in the ocean component of the NCAR Community Climate System Model (CCSM3) so that the time evolving temperature and salinity both to the east and west of a closed off Gibraltar are the only drivers (Wu et al., 2007). In coupled simulations, the challenge is to obtain a stable, realistic solution, when the forcing and modeling of the Mediterranean play an active role over hundreds of years. So that long integrations would be feasible, we used the low (nominally 3 degree) resolution (T31x3) version of CCSM3 (Yeager et al., 2006). Detailed comparisons of solutions after

300 years from control simulations with a blocked Strait of Gibraltar and from experiments with the PMO for ocean-only and coupled cases are presented in Wu et al. (2007).

After spin-up, the volume transports of the source water with PMO are 0.74 and 0.84 Sv in ocean-only and coupled simulations, respectively. The volume of entrained North Atlantic water is 0.96 and 1.03 Sv, respectively, in ocean-only and coupled simulations. Both the source and entrained water transports remain at the lower limits of observational estimates. Similarly, the product water transports fall below the observational range to 1.70 (ocean-only) and 1.87 Sv (coupled). These transports are undoubtedly sensitive to both the atmosphere and ocean models, and to obtain such reasonable results at low resolution is encouraging.

Figures 8a and 8b compare the PMO and control results for year 30 of the ocean-only simulations. The Mediterranean Salt Tongue is completely missing in the control integration. In contrast, it is clearly present in the PMO simulation. In comparison with the observations (Fig. 8f), the PMO tends to produce a saltier and warmer salt tongue.

A parallel track to the implementation of the MSBC in the CCSM has been the implementation of new developments in the GFDL isopycnal model GOLD. Prior to the CPT, this model used the TE shear-driven mixing parameterization. The Strait of Gibraltar was set to the size of the model grid, 111 km, much wider than the actual straits. In this configuration there was an overly strong exchange through Gibraltar, roughly 5 Sv averaged over the first year, that leads to a strong salty drift in the MOW and a fresh drift in the Mediterranean (figure 8c). Restricting the width of Gibraltar to its true width of 12 km, using a new algorithm for ”partially open barriers” which allows for channels of sub-grid-scale width, immediately reduces the transport through the channel to realistic levels. However, with just the TE parameterization, the MOW develops two plumes - one that exhibits reasonable levels of entrainment, and a second plume of nearly undiluted overflow water within the bottom Ekman layer (figure 8d). This separated deeper plume is eliminated by using the HBBL parameterization (figure 8e). With these two improvements in place, the overflow plume has a salinity, density and volume much closer to that seen in observations (figure 8f).

The future of this and other Climate Process Teams

We have described here how the Gravity Climate Process Team effort has led to new parameterizations of processes active in overflows, and how implementation of those parameterizations in the Mediterranean overflow have led to significant improvement of climate model simulations in comparison with observations. Similar approaches have been taken to develop improvements for the Nordic overflows and Red Sea overflow, where results from regional simulations (Riemenschneider and Legg, 2007; Pratt et al., 2007; Chang et al., 2008) are being used to guide the implementation of parameterizations in OGCMs. Finally, work is currently underway to translate these improvements to the Antarctic overflows.

An important goal of the CPT is to evaluate the impact of overflow processes on the climate. This is only now becoming possible, as overflow parameterizations are implemented into coupled climate models. However, work carried out in idealized ocean models suggests that overflow entrainment can significantly influence the Meridional overturning circulation and large-scale ocean stratification (Hughes and Griffiths, 2006; Wahlin and Cenedese, 2006). The next step will be to examine the influence of the overflows in OGCMs. Early results suggest that much of the North Atlantic is impacted by the overflows, with changes in the deep western boundary current leading to changes in the overlying Gulf Stream and hence influencing air-sea heat transfer. Future work will examine the role overflows play in variations in the Meridional Overturning Circulation, whether as a result of increased fresh-water input or in past climate scenarios.

This CPT was one of three pilot CPTs, and it is hoped that future CPTs will follow. The success of this CPT would not have been possible without the serious input and effort of observationalists and process modelers, combined with the involvement of multiple modeling teams. The CPT workshops and special sessions at large conferences have played an important role in encouraging this dialog. Importantly, several ideas for parameterization, e.g. the MSBC and the TE mixing parameterization, were already formulated before the start of the CPT, so that real progress was possible in implementing parameterizations into climate models during the short time-line of the CPT. The pursuit of several different avenues for parameterization has been important in ensuring diversity of approach, and encouraging new solutions. The CPT style of collaboration between model developers, process researchers and field observationalists is one which has worked well, we believe, and has gone some way to ensure that our best present understanding of overflows has been incorporated into the development of OGCMs in a timely way.

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List of Figures

	Faroe Bank	**Denmark St**	**Ross Sea**	**Weddell Sea**	**Red Sea**	**Med Sea**
Source Water						
Potential temp. degC	0	0.25	-1.9	-1.9	22.8	14.0
Salinity	34.92	34.81	34.8	34.67	39.8	38.4
σ_0	28.07	27.94	27.9	27.8	27.7	28.95
sill depth (m)	800	500	600	500	200	300
Product Water						
potential temp. degC	3.3	2.1	-1.0	-1.0	21.7	11.8
Salinity	35.1	34.84	34.72	34.67	39.2	36.4
σ_0	27.9	27.85	27.85	27.75	27.48	27.6
depth (m)	3000	1600	>3000	2000	750	850
Transport (Sv)						
Source	1.8	2.9	0.6	1.0	0.3	0.8
Product	3.3	5.2	2	5	0.55	2.3
Velocity U (m/s)						
Source	1	0.7	1	1	0.55	1
Product	0.5	0.4	0.5	0.4	small	1
Thickness H (m)						
Source	200	200	150	100	100	200
Product	150	200	250	300	140	200
Transit time, source to product (days)	3-5	4-7	1	1	3.5	3-5
Tidal current (m/s)	0.2	0.1	0.3	0.2	0.8	0.1
$g' = g\Delta\rho/\rho_0$		2×10^{-3}	2×10^{-3}	2×10^{-3}	1.4×10^{-2}	1.6×10^{-3}
Froude number $Fr = U/\sqrt{(g'H)}$	1	0.3-1.2	0.9-1.1	1	0.6-1.3	1
Entrainment rate W_e/U	5×10^{-4}	1×10^{-3}	6×10^{-3}		2×10^{-4}	5-20$\times10^{-4}$
Coriolis parameter f (s^{-1})	1.3×10^{-4}	1×10^{-4}	1.3×10^{-4}	1.3×10^{-4}	1.3×10^{-5}	3.1×10^{-5}
Deformation radius (km) $L_R = \sqrt{g'H}/f$	30	5	7	7	40	100

Table 1: The Observationalists' Table, showing comparison of key parameters in different overflows. The source and product water properties serve as a reference against which to evaluate OGCMs. The parameters at the bottom of the table show that while rotation has varying degrees of influence, in all the overflows the Froude number can exceed 1, in regions associated with entrainment.

Model name	Vertical coordinate	Type of simulation	Gravity current Parameterization/ Representation	CPT references
HYCOM	Hybrid isopycnal/ pressure	Process study; regional; large-scale	TPX MSBC	Chang et al. (2005), Chang et al. (2008), Xu et al (2006,2007)
MITgcm	pressure	Process, regional	resolved; numerical diffusion	Legg et al. (2006,2007) Riemenschneider and Legg (2007)
POMgcs	Terrain-following/ Generalized	process	M-Y	Ezer and Mellor (2004) Ezer (2005) Ezer (2006)
MOM4	pressure	global	Campin-Goose cross-land diffusion Beckmann-Doscher	Griffies et al. (2005) Gnanadesikan et al. (2006)
CCSM	pressure	global	MSBC	Wu et al. (2007), Yeager et al. (2006)
HIM/GOLD	isopycnal	process, global	JHS HBBL	Legg et al. (2006,2007) Legg et al. (2007)
Nek5000	Terrain-following	process	resolved	Fischer (1997) Özgökmen et al. (2004a, 2004b, 2006)

Table 2: The different ocean models which have participated in the CPT. For details of the model configurations and parameterizations used, see the references listed. The model acronyms are defined as follows: HYCOM: HYbrid Coordinate Ocean Model; MITgcm: Massachusetts Institute of Technology general circulation model; POMgcs: Princeton Ocean Model generalized coordinate system; MOM4: Modular Ocean Model version 4; CCSM: Community Climate System Model; HIM: Hallberg Isopycnal Model, now superceded by GOLD: Generalized Ocean Layer Dynamics model; Nek5000: parallel spectral element nonhydrostatic model. The parameterization acronyms are: TPX: extended Turner parameterization (Xu et al., 2006); MSBC: Marginal Sea Boundary Condition; M-Y: Mellor and Yamada (1982); JHS: Jackson-Hallberg scheme; HBBL: Hallberg Bottom Boundary Layer model.

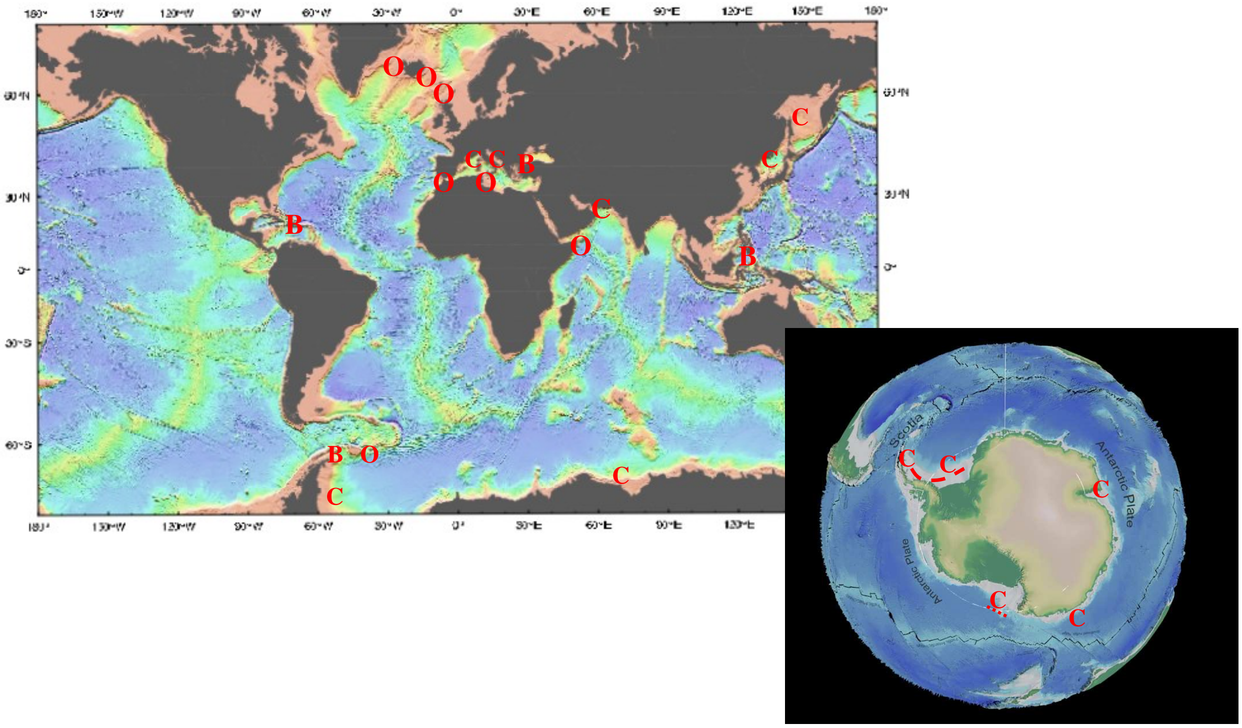


Figure 1: Location of major gravity currents by type: O: Overflow across a topographic barrier from a regional basin into the open ocean, e.g. the Nordic overflows, Red Sea overflow and Mediterranean overflow; B: Open ocean overflow into an isolated regional basin; C: Cascade of dense water from a continental shelf, e.g. the Ross Sea and Weddell Sea overflows. See Table 1 for further information. Not shown are numerous overflows across multiple sills of the mid-Ocean ridge system, within the series of basins of the western South Pacific, and the cascades of shelf water over the slope of the Arctic sea. Bathymetry map from Smith and Sandwell, 1997

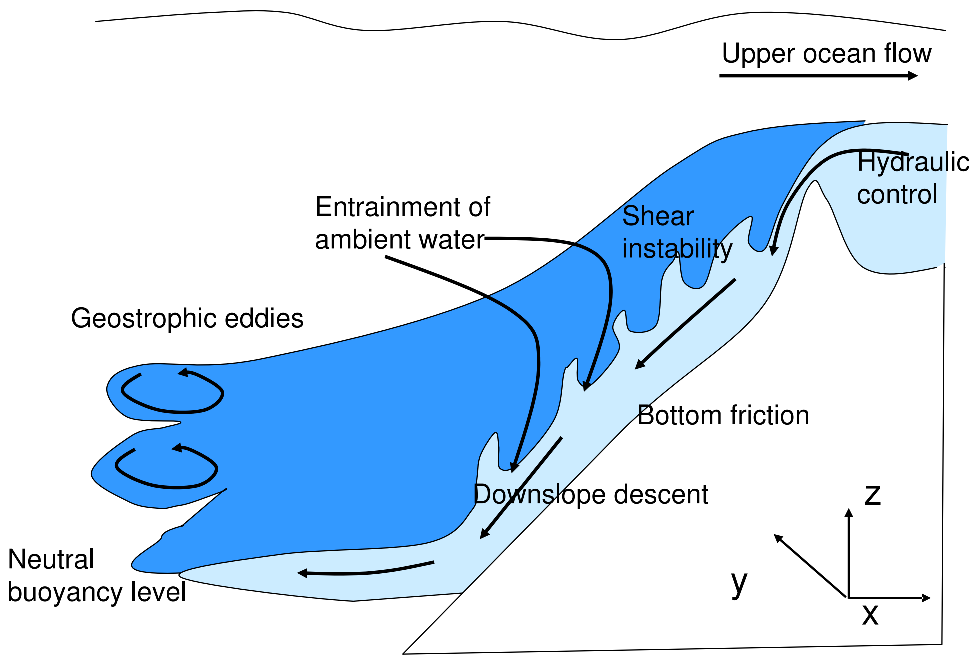


Figure 2: Physical processes acting in overflows

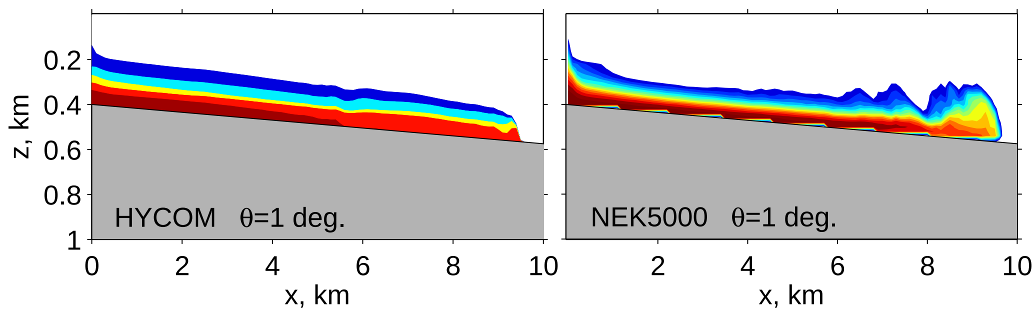


Figure 3: Snapshots of salinity distributions from HYCOM (left panel), using the TPX parameterization, with a horizontal resolution of $\Delta x = 100m$ and 6 isopycnal layers and Nek5000 (right panel) nonhydrostatic simulations with a horizontal resolution of $\Delta x = 33m$, and vertical resolution of $4m < \Delta z < 10m$, in idealized bottom gravity current experiments over smooth topography with a slope of $\theta = 1°$.

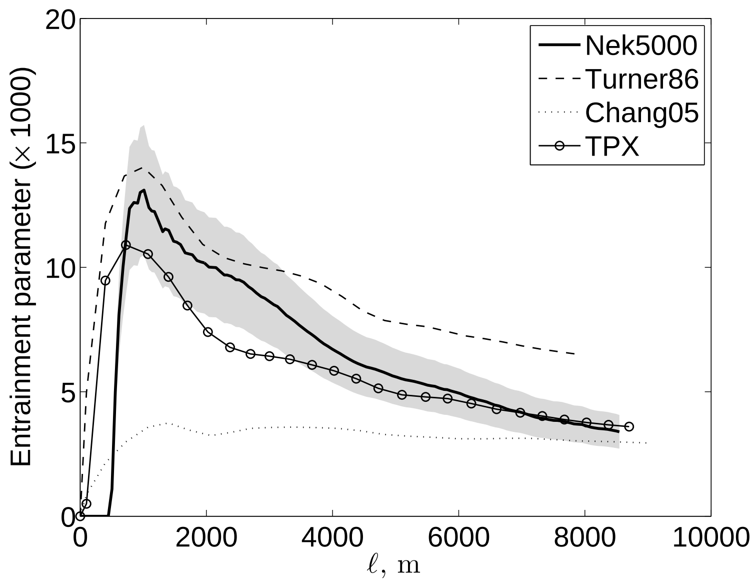


Figure 4: Comparison of the entrainment metric $E \equiv (h - h_0)/\ell$, the ratio of the difference between the average and initial thicknesses of the plume and the plume length, from Nek5000 and HYCOM using different entrainment parameterizations: $E = (0.08 - 0.1Ri)/(1 + 5Ri)$ based on Turner (1986), $E = 0.15(0.08 - 0.1Ri)/(1 + 5Ri)$ from Chang et al. (2005) and $E = 0.2(1 - Ri/0.25)$, the TPX parameterization, Xu et al. (2006). .

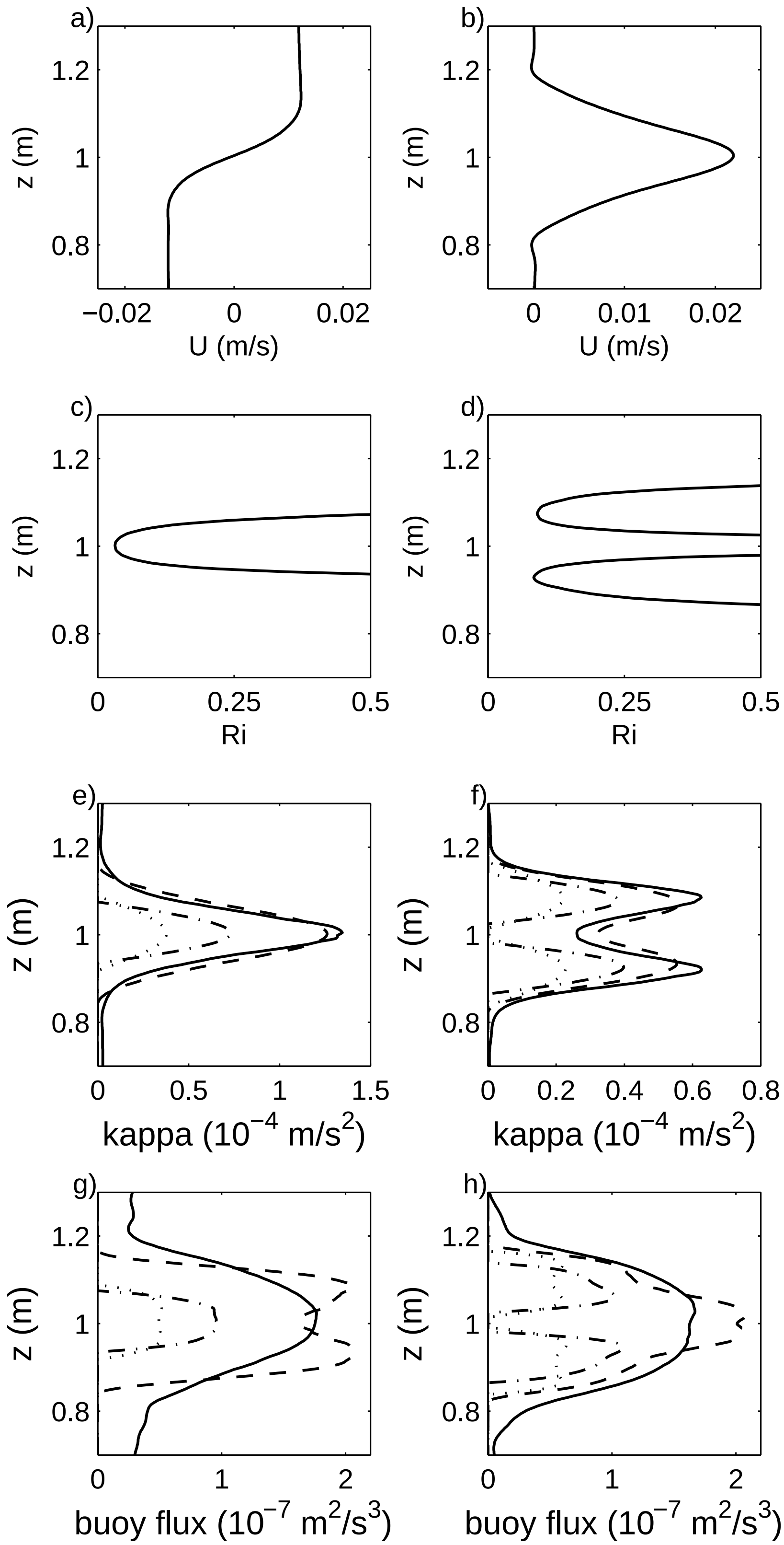
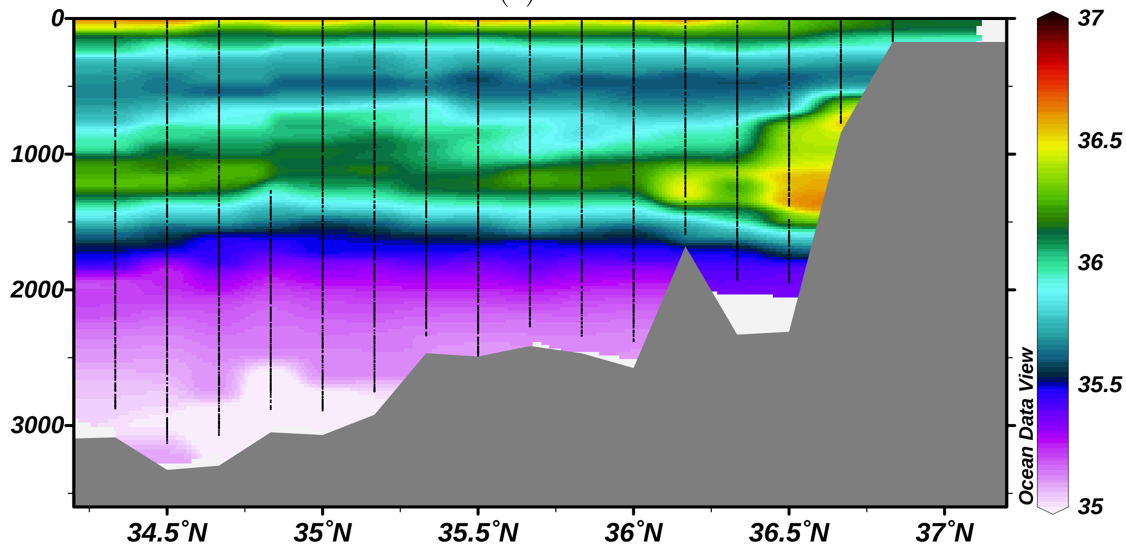


Figure 5: Comparison of parameterizations with high resolution results: a) and b) velocity profiles; c) and d) Richardson number; e) and f) eddy diffusivity; g) and h) buoyancy flux. Shown in e-h)a are: results from high-resolution simulation (solid line); TE (dotted line); TPX (dot-dash line); JHS

(a)



(b)

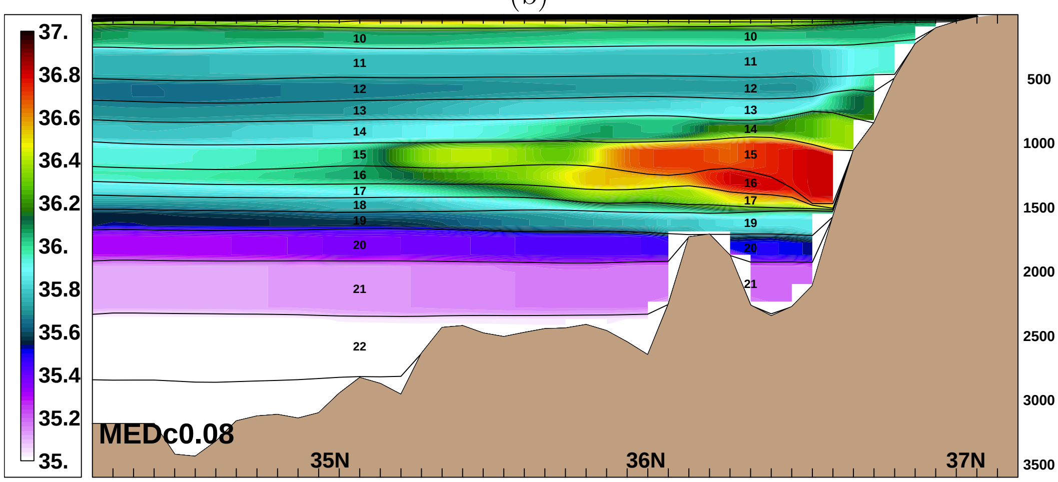


Figure 6: Salinity in the Mediterranean outflow plume shown as a function of latitude and depth along a section at 8.5°W from WOCE observations (top panel) and HYCOM regional simulation at 0.08 degree resolution (bottom panel)

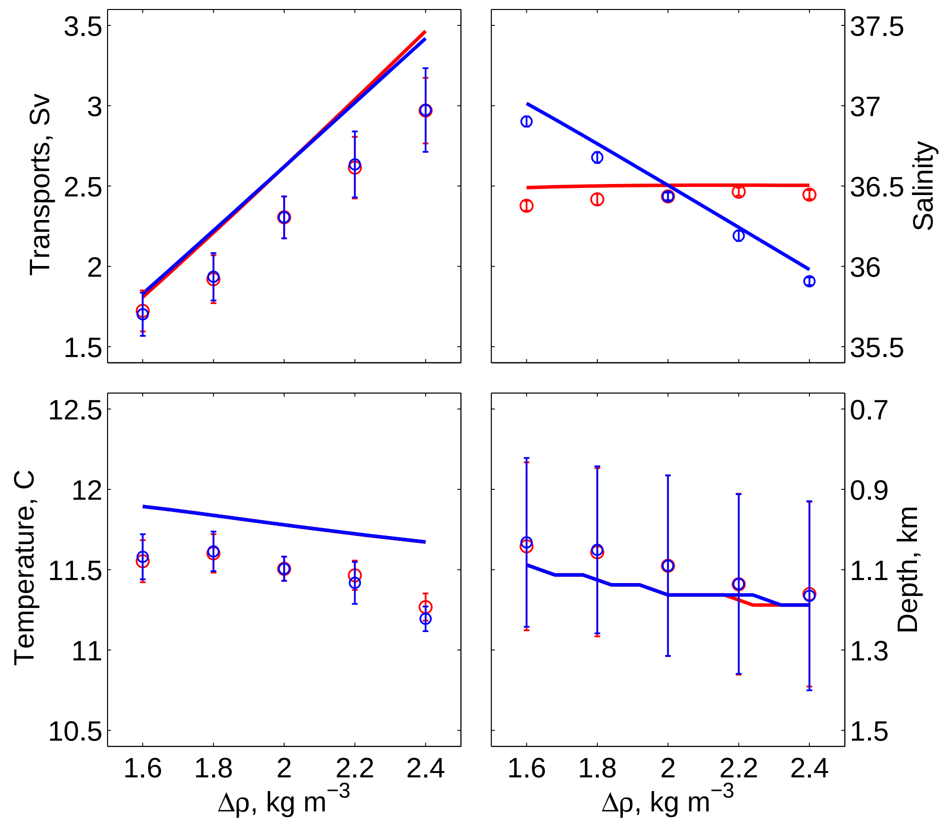


Figure 7: The MOW product water properties as predicted by five HYCOM/TPX experiments (discrete circles) and by MSBC (lines). The abscissa is the density contrast between the Mediterranean Sea and the Gulf of Cádiz. The nominal (modern) value is 2 kg m^{-3}. The density contrast was changed by imposing an increase or decrease of salinity throughout the entire water column in either in the Mediterranean Sea (red circles (HYCOM) and red lines (MSBC)) or in the Atlantic (blue circles (HYCOM) and blue lines (MSBC)). The four panels are the resulting overflow product water transport (upper left), salinity (upper right), temperature (lower left), and equlibrium depth (lower right). The error bars (of HYCOM results) represent the standard deviation for transport, salinity and temperature, and the mean upper and lower interface of outflow plume for depth. Generally the trends of overflow properties are similar in the HYCOM and MSBC results. Unlike most other quantities, product water salinity does not change in a symmetric way with respect to changes in oceanic versus marginal sea properties, and this asymmetry in the salinity response shows up in a very similar way in both models.

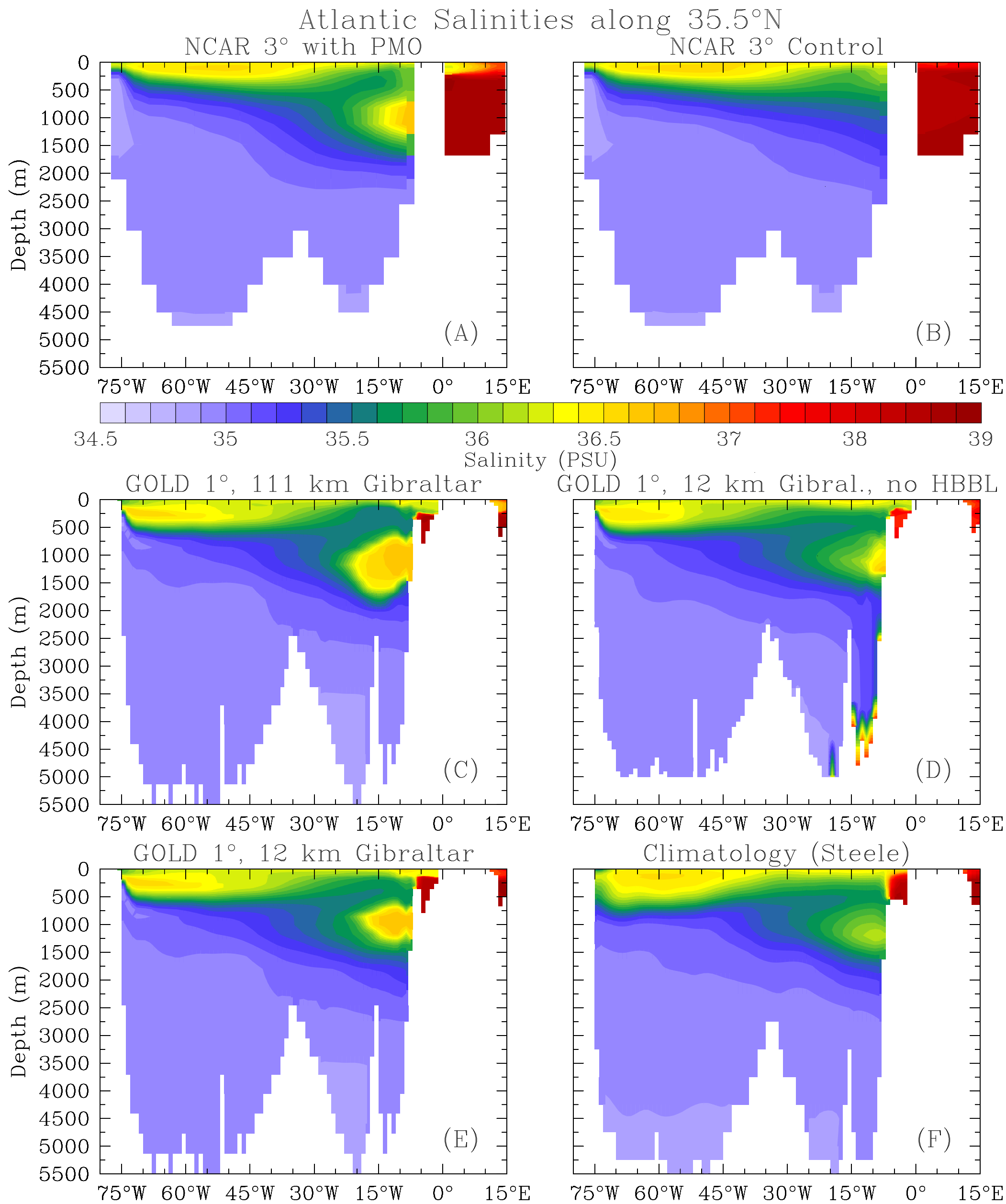


Figure 8: Salinity cross-sections in the Atlantic ocean at the latitude of the Strait of Gibraltar. The top two panels compare the results after 30 years with the NCAR ocean-only simulations with the parameterized Mediterranean outflow (PMO) and a control experiment in which the Strait of Gibraltar is blocked. These simulations use the nominal 3-degree resolution version of the model. The improvements due to the PMO are obvious. The next 3 panels show the results after 5 years in GFDL's 1-degree isopycnal coordinate, GOLD, with Gibraltar open at 111 km (1 grid point) width, with Gibraltar restricted to 12 km but without the HBBL parameterization, and finally with both TE and HBBL parameterizations activated. The final panel shows the salinity in the Steele ocean climatology; the data processing behind this climatology includes enough temporal and spatial smoothing that the "climatological" salinity of the plume is lower by several tenths of a PSU compared with raw profiles, but it should be reflective of the depth and extent of the plume.