Collaborative Research: Gravity Current Entrainment Climate Process Team

1. Introduction

What is gravity current entrainment? Dense water formed through cooling or evaporation in marginal seas (e.g. the Greenland-Iceland-Norwegian sea; the Mediterranean, the Red sea) or on coastal shelves (e.g. the Arctic and Antarctic shelves) enters the general ocean circulation by flowing over topographic features, including narrow channels (e.g. the Denmark Straits, Faroe Bank Channel, Gibraltar Straits, Bab-el-Mandab) and down the continental slope. As the dense water descends under gravitational acceleration, it entrains ambient water, which mixes with the dense flow, modifying the tracer properties and increasing the volume of the dense water mass. This entrainment can be characterized by the entrainment velocity $W_e = (1/L)dQ/dx$ where Q is the volume flux and L is the bounding cross-sectional perimeter of the plume. Ultimately when the dense water reaches a level of neutral buoyancy, downward acceleration ceases, and the water is free to intrude into the ocean interior. Entrainment is a bulk characterization of the poorly understood turbulent mixing against the stabilizing effects of stratification, and may be expressed in terms of external parameters, such as the density difference with respect to the overlying fluid, the thickness of the entraining layer, and probably the velocity (mean horizontal current) or velocity shear, δV. The nondimensional entrainment rate is then $E = W_e/\delta V$. The characterization of mixing in an inhomogeneous environment by a nondimensional entrainment rate has proved very useful as both a modeling/parameterization tool and a diagnostic in flows such as the deepening oceanic mixed layer and atmospheric convection, and for this reason we regard it as a convenient starting point for gravity currents.

Why is gravity current entrainment important? The net volumes, tracer properties and final depth of the new water mass entering the deep ocean circulation are highly sensitive to the amount of entrainment that has taken place. Since the dense water masses formed through entrainment into gravity currents (e.g. North Atlantic Deep Water, Mediterranean overflow water, Antarctic Bottom Water) fill much of the deeper ocean, entrainment ultimately determines the properties of much of the abyssal water masses, which may be quite different from those of the source waters which overflowed the sill. For example, the density ordering of four major source waters, i.e., Filchner Ice Shelf Water, Denmark Strait source water, Faroe Bank Channel source water, and Mediterranean source water, is the reverse of the density ordering of the final product waters that enter the open ocean (Price and Baringer, 1994). Hence entrainment influences the climate through the role that these water masses play in the thermohaline circulation.

Possible Climate Impacts The combination of dense water from Denmark Straits overflow and the Faroe Bank Channel ultimately forms North Atlantic Deep Water, which flows Southward as the deep Western Boundary Current through the Atlantic, forming the deep return branch of the thermohaline circulation. Any changes to these deep overflows will therefore ultimately influence the thermohaline circulation. One such change to overflow waters, and the downstream properties of the deep western boundary current is currently taking place (Dickson et al, 2002), and there is significant speculation that this may signal a rapid climate transition.

Idealized simulations of the thermohaline circulation (Price and Yang, 1998; Lohmann, 1998) show that when deep water is formed in a marginal sea and enters the open ocean through an overflow, the thermohaline circulation is less likely to be shutdown by a fresh water anomaly, than for simulations where all deep water is formed through open ocean convection. Wood et al (1999), using the Hadley center model with a bottom boundary layer scheme show that overflows are much more robust to CO2 perturbations than the upper parts of the thermohaline circulation. Sensitivity to better representation of Denmark Straits (i.e. artificial deepening of the model sill topography) has also been seen in the meridional circulation in NCAR coupled climate simulations.

Hence we believe there is evidence that improved representation of overflows in climate models will have a significant impact on the the mean states of climate simulations, and, perhaps more importantly, on the reliability of climate model forecasts of abrupt climate changes involving the deep ocean circulation.

2. Scientific Background

Given that overflows are in the category of strongly-stratified, fast shear flows the entrainment parameter is often given as a function of a bulk Richardson (Ri) or Froude ($Fr = Ri^{-1/2}$) number (e.g., Ellison and Turner, 1959; Baringer and Price, 1997). A central objective of this proposal is to examine the functional form of this relationship $E(Fr)$.

Entrainment relationships may be deduced from laboratory experiments, dedicated observational programs for oceanic overflows, and high resolution nonhydrostatic numerical simulations, each of which has its own advantages and disadvantages. Hence we believe that a team combining process modelers (Legg, Özgökmen, Yang) with observationalists (Price, Peters, Gordon) and large-scale modelers (Chassignet, Schopf, Ezer and modeling center teams) will combine the strengths of these different approaches to make most efficient progress in the difficult problem of parameterization of gravity currents.

2.1 Physical processes responsible for entrainment

The characterization of entrainment in terms of a Fr or Ri was suggested by Ellison and Turner (1959, ET 59) and is used here in Figure (1) where a number of natural and laboratory scale measurements of entrainment rate are plotted vs. Fr. Individual symbols refer to natural flows; the Mediterranean outflow (Baringer and Price, 1997), and a turbulent saline density current that flows periodically into Lake Ogawara Japan (Dallimore et al. 2001). Shaded regions encompassing a cloud of data points are shown for 3 laboratory flows, which span a much larger range of Fr than do the natural cases. However, the lab flows may not be fully turbulent (the ET 59 data) or they are not density-driven currents, though they are stably stratified and have a well-defined Froude number (Loftquist, 1960; L 60). The data cloud A 86 is a moderately large Re (industrial) flow described in Dallimore et al. (2001).

We note that: 1) There is a broad consistency among the various data sets that in the vicinity Fr = 1 the entrainment rate is about 1×10^{-3}, a significant entrainment rate for oceanic density currents. 2) Most of the data (with L 60 being a partial exception) indicate a very steep increase of the entrainment rate with increasing Fr at $Fr = 1$. The dashed line is $E = 1 \times 10^{-3} Fr^8$, which is adequate very near $Fr = 1$, but clearly goes too high for Fr values that exceed 1. A far messier but more comprehensive 'law', is the solid line labeled EL,

$$E = \frac{1 \times 10^{-3} Fr^8}{1 + 12 \times 10^{-3}(Fr + 0.4)^8},$$

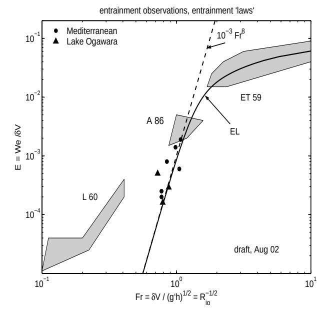

Figure 1: Entrainment observations from natural flows (single points) and from laboratory experiments or laboratory-scale flows (shaded clouds that encompass a number of data points). Of the latter, the ET 59 data are at the smallest Reynolds number.

which asymptotes to the neutral jet value, $E = 0.08$, noted by Ellison and Turner (1959). We expect entrainment to asymptote to a finite value at large Fr but the appropriate value for an oceanic density current is unknown.

This result EL can be used within a layered ocean model that simulates currents and the density of an outflow, and seems to give a plausible simulation of the density changes that occur along oceanic outflows (Price and Baringer, 1994; Hallberg, 2000). While an entrainment law of this sort may be quite useful as a bulk characterization of mixing, it gives only vague clues to the mechanism(s) of mixing. The collapse of the data implies that the mean shear due to the density-driven flow is the primary source of turbulence; but this entrainment law does not discriminate between shear at the interface or that due to bottom stress. 'Entrainment' may have to be qualified - recent measurements in the Red Sea outflow revealed that while the upper part of the outflow mixed vigorously and did show entrainment, the lower part near the bottom remained virtually undiluted over significant distances (Peters et al., in preparation 2003). Numerical simulations of this overflow display intense internal wave activity, in particular roll waves, hydraulic jumps, laminar wavetrains etc. (Özgökmen et al., 2003).

Many studies indicate greater complexity in gravity currents than is contained in the $E(Fr)$ model. Examples of other important dependencies include (1) downstream location (Pawlak and Armi (2000)); (2) ambient stratification (Baines, 2001) which induces continuous detrainment (i.e. loss of dense fluid from the fast moving current) over the descent of the plume at a rate dependent on a nondimensional combination of flow rate and ambient buoyancy frequency; (3) rotation, which enables several different regimes: Ekman drainage in a thin layer with little mixing (Condie, 1995); roll waves leading to entrainment through wave breaking (Cenedese et al, 2003); and finite amplitude geostrophic eddies (Lane-Serff and Baines, 1998) which carry fluid across isobaths (Jiang and Garwood, 1996 and Gawarkiewicz and Chapman, 1995) and may also lead to stirring with ambient fluid (currently under investigation by Legg, Cenedese, Girton). Additionally more localized mixing could take place within internal hydraulic jumps downstream of hydraulic control points, such as found in the constrictions through which many dense currents pass. While mixing in non-rotating hydraulic jumps is well studied (Hornung et al, 1995; Hoyt and Sellin, 1989, Scinocca and Peltier, 1993), with rotation transitions from supercritical to subcritical flow may occur through lateral jumps (Pratt, 1987) or through less shock-like transitions, perhaps with less mixing (Karl Helfrich, private communication).

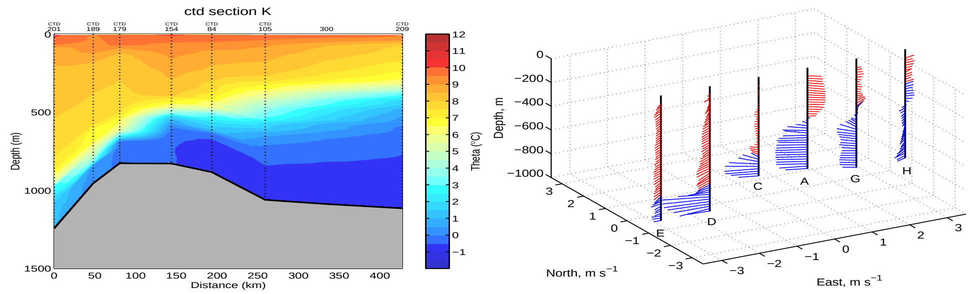

Figure 2: (Upper) A section of potential temperature made up from CTD stations taken along the path of the Faroe Bank Channel outflow. The Norwegian-Greenland Sea is to the right, and the northern North Atlantic is to the left. (Lower) A 3-d perspective view of XCP-measured currents along the path of the outflow.

In summary, the only existing parameterizations of gravity current entrainment in use in GCMs (based on Ellison and Turner 1959) exclude much of the phenomena associated with dense currents - detrainment in stratified ambients, roll waves, Ekman drainage, eddy-related processes, and mixing associated with hydraulic jumps.

2.2 Field Data and their analysis

To get some qualitative sense for the mixing process we have to take a much more detailed look at field data, and then interpret the field data in the light of laboratory and numerical simulations. This interpretive stage that would benefit greatly from the collaboration between observationalists and CPT modelers. Here we highlight 4 regions where recent observations of density driven currents have been made. In addition to these data sets, data from the Mediterranean outflow plume (Price et al, 1993) will also be used for model validation.

Faroe Bank Channel An analysis of the Faroe Bank Channel outflow is underway at present, by J. Price, T. Sanford, C. Mauritzen and M. Prater. Faroe Bank Channel (FBC) is the deepest passage between the Norwegian-Greenland Sea and the North Atlantic Ocean and is the site of a quasi-steady outflow of dense water from the Norwegian-Greenland Sea into the northern North Atlantic. Under NSF sponsorship, we (Price, Sanford, Mauritzen and Prater) conducted a field survey of FBC, with the goal to acquire finely sampled measurements of currents and hydrography in the region several hundred kilometers up and downstream of the sill in FBC sufficient to answer several questions, including: Where and how does mixing occur in the descending outflow? A report of much of the data is available on line from the web site noted in Price et al. (2001).

A synthetic, longitudinal section, made up of stations that were in the core of the outflow (maximum density and maximum thickness) shows that the hydrographic properties (temperature (Figure 2), salinity, oxygen) of the outflow current change as the water outflows the sill in Faroe Bank Channel and descends into the northern North Atlantic. Along the path of the outflow current the temperature of the deepest (and densest) outflow water changes in what appears to be a gradual manner from about -1 C within the Faroe Shetland Trough to about 3 C a hundred kilometers or so to the west of the Faroe Bank Channel (the shallowest region on this section). The accompanying increase of salinity, and decrease in oxygen concentration all indicate that the changes in outflow

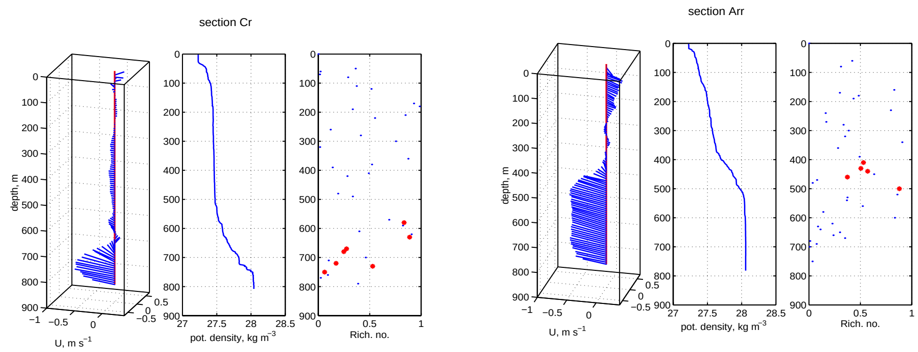

Figure 3: (Left) XCP and CTD profile data taken in a region of significant mixing of the outflow layer. (Right) XCP and CTD profile data taken near the center of the narrow portion of Faroe Bank Channel. The gradient Richardson number is computed by vertical differencing over an interval of 10 m.

water properties are due mainly to mixing with the warmer, saltier and less oxygenated North Atlantic water overhead.

Figure 3 shows the gradient Richardson number within the upper (interfacial) boundary layer is low, approx 1/2, over a strongly stably stratified layer several tens of meters thick. Farther downstream Figure 3 (left), where the outflow has broadened by a factor of almost 5, and has begun to descend the continental slope, the gradient Richardson number is lower, very roughly 1/4 over a thick layer of stratified outflow water. In this region the increase of temperature and the increase of transport implies significant entrainment, while upstream the mixing would probably better be described as local vertical mixing at the upper interface with North Atlantic water. It remains to be seen whether these FBC data will indicate a similar entrainment rate dependence upon Fr as seen in Figure (1).

Red Sea Outflow The outflow of salty and heavy water from the Red Sea into the westernmost Gulf of Aden differs from other outflows in its pronounced seasonal variability (Murray and Johns, 1997), low latitude (ca. 12N), and sea floor topography. When the Red Sea plume exits from the Strait of Bab el Mandeb it continues downslope toward the Tadjura Rift with a rim depth slightly below 800 m, flowing mainly along two channels. The 130 km long “Northern Channel” (NC) is topographically heavily confined and narrow. The typical width of 5 km at the plume level is much smaller than the internal radius of deformation, indicating that the descending plume in the NC is sheltered from the effects of the Coriolis force. In this channel the Red Sea plume shows an interesting dichotomy between lack of entrainment and intense mixing (Peters et al. in preparation 2003). A 30–100 m thick weakly stratified “bottom core layer,” reaching up to the velocity maximum, shows little dilution along the channel, the winter season salinity dropping along the 130 km path only by about 0.2 psu. Hence the core bottom layer undergoes little entrainment, a conclusion also true during the weaker summer outflow. In contrast, a 40-300 m thick “interfacial layer” undergoes vigorous mixing as quantified on the basis of turbulent overturning scales (Thorpe scales; Thorpe, 1977) extracted from regular CTD profiles. A typical value of the estimated eddy diffusivity is 10^{-2} m^{2}s^{-1}, and the average estimated turbulent salt flux is 10^{-4} kg m-2s^{-1}. Gradient Richardson numbers (Ri) in the thick interfacial layer were greatly variable with extensive areas of subcritical values, $Ri < 1/4$. The relationship of the plume with bulk Richardson numbers has not yet been explored. The interfacial gradient layer of the plume carried roughly one half of the total plume transport. In summary, it appears that the Red Sea outflow is not well described by a model of a single, homogeneous, entraining layer. The Red Sea plume does grow vertically in the downstream direction, and this vertical growth is roughly consistent with the observed mixing. The estimated average salt flux of 10^{-4} kg m$-$2s^{-1} can be translated into an entrainment velocity of $w_e = 3 \times 10^{-4}$ m s^{-1} and an entrainment constant $w_e/\overline{u} = 5 \times 10^{-4}$ where $\overline{u} = 0.6$ m s$-$1 is the average plume velocity across core bottom- and interfacial layer. It has to be noted, however, that the quoted w_e and salt flux reside in the interfacial layer, making it the location of "entrainment."

Antarctic slope plumes In Antarctica, dense shelf water is produced around the ocean margin where cold air blows from the continental ice sheet (e.g. Weddell Sea, Ross Sea, Adelie Coast and Amery Basin), and descends to the sea floor at select sites along the Antarctic Slope Front to form Antarctic Bottom Water (AABW) [Gill, 1973; Jacobs 1991; Whitworth et al. 1998]. Entrainment is evident in the 50% increase in transport of AABW ($8.1 \times 10^6 m^3/s$) as compared to that of the descending Antarctic Shelf Water ($5.4 \times 10^6 m3/s$) (Orsi et al 2001, Orsi et al 2002). In addition $4.7 \times 10^6 m^3/s$ of less dense Antarctic surface water [AASW] (found seaward of the slope front) descends to ventilate the deep water layers [Gordon, 1998; Gordon et al, 2001; Orsi et al, 2002] producing $9.4 \times 10^6 m^3/s$ of deep water.

The mechanisms governing the export of dense fluid from the shelf, and hence creating the descending plumes may differ from those in other ocean regions, with synoptic winds, tidal mixing and currents, Benthic layer Ekman dynamics and instabilities of the Antarctic slope front [Chapman and Gawarkiewicz, 1995; Gawarkiewicz and Chapman, 1995; Condie, 1995; Jiang and Garwood, 1996] playing a possible role. The descending plumes, which appear as strong near bottom gradients [Whitworth et al. 1998; Gordon, 1998; Rintoul, 1998] may be concentrated in submarine canyons or within thin, eddy rich sheets over a smoother slope [Baines and Condie, 1998]. Once released from the shelf the descending plumes entrain ambient, warmer slope water, to reach the AABW product.

Nonlinearities in equation of state likely play an important role in Antarctic plume processes. While the highest salinity shelf water may descend easily to the sea floor, much of the water with intermediate salinity can only descend to great depths with the assistance of cabbeling [varied dependence of density on temperature; Fofonoff, 1956] or thermobaric [cold seawater has greater compressibility than warm seawater; Gill, 1973; Foster, 1995; Gordon, 1998; McPhee, 2001] effects. The thermobaric effect acts as a positive feedback to cold plume descent over the continental slope, as the reduced gravity increases on continued descent. In addition, the thermobaric effect strengthens the pycnocline capping the plume, which limits entrainment of ambient, warmer offshore water.

Analysis of the Ice Station Weddell and Dovetail data [Gordon, 1998; Gordon et al, 2001] can be summarized as a case study of Southern Ocean plume properties (figure 4). Often observed within the slope plumes is complex layering, with the saline plume slipping below and displacing upward the low salinity variety. This complex layering is also seen in the Ross Sea [A.L.Gordon p.c., based on recent Ross Sea cruise], prompting speculation that high salinity shelf waters plumes may enable the descent of the less dense shelf waters, through entrainment processes aided by the thermobaric effect. Other candidate processes include: geostrophic adjustment (deepening of isopycnal surfaces) of the pycnocline as it enters into the boundary currents of the southern and western Weddell Sea; Ekman veering within the benthic boundary layer; surface ocean Ekman convergence; and cabbeling. The similarity of temperature, salinity and oxygen values within the shelf water and the benthic layer at depths of 2000-m indicates that surface water reaches the sea

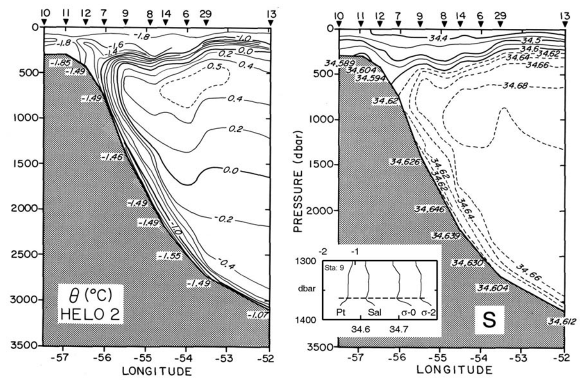

Figure 4: Potential temperature and salinity section in the western Weddell Sea along 68 40'S, obtained in 1992 in full ice cover with a Helicopter CTD (Gordon, 1998)

floor without much dilution. This may be a consequence of the thermobaric effect that shields the plume from entraining and mixing with ambient warmer off shore deep water.

Denmark Straits Overflow Entrainment in the Denmark Strait Overflow has been diagnosed in two ways. The first is the increase in mean transport of overflow water (denser than $1027.8kg/m^3$) from 2.9-5.2 Sv between current meter arrays located 70 km and 200 km downstream of the sill (Dickson and Brown, 1994). The second is from a synoptic survey of T, S and velocity undertaken in 1998, resolving both eddy structures and the mean evolution of overflow properties between the sill and 220 km downstream (Girton and Sanford 2003). Entrainment rates diagnosed from overflow density changes in the survey indicate that the bulk of the entrainment occurs between 125 and 200 km from the sill, coincident with a dramatic increase in transport variability and the production of cyclonic surface eddies visible in satellite SST imagery. The magnitude of entrainment in this region is consistent with the current meter transports. Recent numerical model results (Girton, private communication) suggest that the growing eddies (produced by upper water column vortex stretching as the overflow descends) are primarily responsible for this entrainment through the straining and pinching of the overflow interface. Alternative hypotheses for the increase in entrainment after 125 km include: a) steepening of the continental slope (though not coinciding with an increase in the rate of dense water descent), b) decrease in background stratification, and c) decrease in bulk Richardson number (though this has not yet been established robustly, given the increasing variability in plume velocity and thickness with distance downstream)

2.3 Current state of gravity current representation in climate models

The two general classes of ocean models most actively used for climate studies have very different issues in the representation of entraining gravity currents. Without an explicit representation of the bottom boundary layer (BBL), Z-coordinate models, including MOM and POP, tend to exhibit unphysically strong entrainment as gravity currents descend, unless both the vertical resolution is fine enough to resolve the BBL thickness (of order 10s of meters) and the horizontal grid resolves BBL thickness divided by the slope (of order kilometers) with several grid points (Winton et al., 1998), much higher than currently affordable. To avoid the unphysical entrainment, a variety of BBL parameterizations for Z-coordinate models have been proposed. Both GFDL and NCAR currently use Beckman and Doscher's (1997) prescription of enhanced slantwise diffusion following the bottom (perhaps jumping over many cells in the vertical between adjacent columns) when the stratification following the bottom is convectively unstable. While this does increase the density of the deep water, it is not a plausible description of the dynamics controlling gravity current transport or entrainment. Another approach that has been implemented without widespread disruption in MOM is the proposal of Campin and Goose (1999), in which an unstable stratification along the bottom causes a specified transport off the shelf to be injected at the neutral depth of that fluid, with a horizontal compensating return flow. Again, this is only a caricature of the governing dynamics of a gravity current, but may be appropriate in the limit where model resolution is too coarse to use the resolved scales to determine the behavior of the gravity current. A more physical approach is the inclusion of a distinct full-dynamics bottom boundary layer model, appended to a Z-coordinate interior (e.g. Killworth and Edwards, 1999). This allows a physically consistent prescription of the subgridscale entrainment by gravity currents, but at the cost of pervasive changes to the Z-coordinate model and the introduction of pressure gradient errors and the other numerical difficulties of sigma coordinate ocean models. While promising, this appended BBL approach will require careful evaluation against oceanic observation, laboratory studies, and numerical process studies before it is well enough understood to be viable for climate studies. The costs and benefits of each of these approaches need to be fully evaluated. Both GFDL and NCAR recognize the desperate need for a vastly improved physical fidelity in the gravity current parameterizations in their Z-coordinate models, in order to make more reliable predictions about changes to the thermohaline circulation. Before settling on an improved parameterization there must first be confidence in the physical reliability of the parameterizations, and that the parameterizations do not introduce new difficulties that outweigh their benefit.

Isopycnic coordinate models, such as HIM, HYCOM/MICOM, and Poseidon, have vertical resolution that naturally migrates to the density front atop a gravity current and do not require a deviation from the underlying model framework to capture the structure of the gravity current (Hallberg, 2000). Moreover, the difficulties with implicitly solving for the vigorous entrainment that occurs at the top of a gravity current have been surmounted (Hallberg, 2000). This class of models has been shown to produce plausible simulations of the Gibraltar plume of Mediterranean water, including approximately the correct level of entrainment although such models do show sensitivity to such key parameters as the entrainment rate and the critical Richardson number, within a plausible range of values (Papadakis et al., 2003). The parameterizations that have been used thus far date back to laboratory work by Ellison and Turner (1959). There is every reason to expect that a more accurate parameterization of gravity current entrainment (including, for example, the effects of rotation or an ambient stratification) can be deduced from additional process studies and validated against oceanic observations. Isopycnic models (or hybrid models that are essentially isopycnic at depth) are able provide the requisite information about the large-scale structure of a gravity current for improved parameterizations, and should be suitable for adopting and evaluating new parameterizations without excessive efforts. Isopycnic ocean models will be increasingly used for climate studies at GFDL and NASA/GISS within the next 2 years, and provide a valuable complement to the traditional Z-coordinate models, especially in evaluating the impacts of gravity currents. Of course isopycnic models have other difficulties and all classes of models have errors introduced by uncertainties in atmospheric forcing.

In summary, recent laboratory and numerical experiments have elucidated many physical processes not included in current model representations of overflows, and recent field programs have provided unprecedented observational evidence of entrainment in oceanic flows. This is therefore an ideal time to combine the theoretical, experimental and observational expertise of those represented in our team with the skills of the climate modeling centers to develop improvements in representation of overflows for the climate models of the near future.

3. Proposed work

Our principal goal is the development and verification of new parameterizations of entrainment in climate models. We are not proposing new process studies or field programs, but we will take a closer look at results from ongoing or completed process studies and observations, with a view to better characterizing the entrainment. To this end we have assembled a team which includes observationalists active in several key programs in recent years: Price (Faroe Bank Channel), Peters (Red Sea Overflow), Gordon (Antarctic); process modelers active in examining entrainment in idealized scenarios (Ozgokmen and Legg) and those with expertise in developing parameterizations (Price and Yang). We are joined by developers of climate-scale GCMs of several different architectures (e.g. Hybrid coordinate, Isopycnal, z-grid, sigma coordinate): Chassignet, Schopf, Hallberg, Danabasoglu, Griffies, Large, and Ezer. A key aspect of our plan is the inclusion of a wide community of process modelers and observationalists as well as representatives of other large scale modeling groups (e.g. MITgcm) through annual workshops.

Our approach is to focus on the problem in several different stages, some of which are concurrent, some sequential.

Stage 1: Evaluation of entrainment in observations Many of the field programs have already involved evaluation of entrainment in the observed flow. Here our emphasis will be on compilation and comparison of these results. We will focus in particular on the comparison between different regions. Questions to be addressed include: Are there qualitative differences in structure, processes and dynamics of different plumes? How important is rotation as a modifying factor in plume dynamics? For example, is the gradient current on the broad slope of Denmark Strait different from the confined current in the "narrow channel" in the Red Sea outflow south of Bab el Mandab Strait? We will involve our active collaborators, and other members of the community in this comparison as much as possible, with this topic forming the core of the first workshop. Members of the team who will take particular responsibility for the evaluation of entrainment in the observations are Price (Faroe Bank Channel), Peters (Red Sea Overflow) and Gordon (Antarctic slope plumes), with participation from our active collaborator Girton (Denmark Straits overflow), and others.

Stage 2: Determination of factors influencing entrainment in observations and process study models This phase of the project will be one primarily of consolidation and comparison of previous or ongoing observational and process studies. Investigators involved in process studies and observations (e.g. Legg, Price, Peters, Ozgokmen, Gordon from the core PI group) will characterize the entrainment $E = W_e/\delta V$ from their own studies and other previously documented studies in terms of the relevant nondimensional parameters. In addition to the Froude number already discussed, other parameters might include dependence on the ambient stratification, the topographic slope and roughness, the Rossby number and the Reynolds number. The relative contribution of different physical processes such as Kelvin-Helmholtz billows, Holmboe waves (that tend to appear when the input density profile is nearly constant and slope angle is high), intenval waves (that tend of appear when the input density profile is linear and the slope angle is small), hydraulic jumps and mesoscale eddies to entrainment will be examined by Ozgokmen and Legg from their high resolution simulations. Another important question we will consider is the extent that the mixing can be characterized as entrainment - i.e. how well mixed is the gravity current, and how much detrainment might be occurring under different conditions? This stage of our project will principally involve examination of results from previous work. For example Legg is currently carrying out nonhydrostatic simulations of entrainment and mixing in rotating hydraulically controlled flows, under NSF funding. Girton and Legg are performing 3D nonhydrostatic simulations of rotating gravity currents in a regime dominated by mesoscale eddies. Ozgokmen has performed several 2D simulations of gravity currents (Özgökmen and Chassignet (2002), and Özgökmen et al. (2003)) and will extend these calculations as far as time allows to better characterize the roles of different structures (e.g. Kelvin-Helmholtz billows, Holmboe waves, internal waves) in determining the entrainment. A motivating question for these studies is: What poses a physical explanation for an entrainment law?

These results will be communicated at the first workshop focusing on entrainment in the observations and process studies. We would aim to compile the results from completed studies as soon as possible, with continuing analysis of results from future and ongoing studies whenever available.

Stage 3: Examination of current parameterizations. Extension of parameterizations/ development of new ones to include new understanding gained from stages (1) and (2) Following Stages 1 and 2, existing parameterization schemes will be examined for their ability to reproduce these entrainment results. The principal starting point is the Ellison and Turner parameterization of entrainment, which is incorporated into the Price-Baringer streamtube model, and implemented in isopycnal models. An initial focus will be: What physics is this model of entrainment missing? (e.g. detrainment, eddy-stirring, hydraulic jumps). Simple conceptual models of these missing processes will be developed and implemented initially in the Price-Baringer model. This model will be modified to (a) include detrainment in a stratified ambient (as suggested by Baines, 2001); (b) include entrainment rates that are modified at low Rossby number; (c) include entrainment rates that vary spatially (as suggested by Pawlak and Armi). These new parameterizations of entrainment will be assessed by comparing the streamtube model with results from both the laboratory and numerical process studies, and by comparison with entrainment rates in the observations. One question to be considered when comparing with observations is how useful bulk models, such as entrainment, can be, given that in the Red Sea for example a thick interfacial layer carries much of the transport. Perhaps turbulence closure models might be more appropriate in such scenarios (e.g. Jungclaus and Mellor, 2000), but a critical assessment of their performance in geophysical gravity currents in still outstanding even though explanations for their earlier problems with stratified flows have been given (Baumert and Peters, 2000) This task will be carried out by the WHOI postdoc, under supervision from Legg, Yang and Price, with Peters consulting on turbulent closures.

A second element of development of parameterizations is the implementation in GCMs. For isopycnal coordinate models we expect that many of the required modifications are likely to be confined to the prescriptions for diapycnal mixing and vertical viscosity, following the formalism of Hallberg (2000). A postdoc at Miami, under the supervision of Chassignet and Ozgokmen, will focus on the implementation of new developments in parameterization into the isopycnal/hybrid class of models represented by HYCOM.

The required modifications to the Z-coordinate models will (CCSM-POP, GFDL-MOM, and MIT) probably need to be more extensive, as there may be horizontal and vertical changes, and even wide-scale changes to the momentum equations. Existing formalisms (e.g. Beckman and Doscher; Killworth and Edwards, 1999) will be examined for their ability to include the entrainment physics. Killworth and Edwards, since it includes entrainment and detrainment parameters, is probably the scheme which can best incorporate the new representations of entrainment. Another possibility is to artificially separate ocean basins, and provide the input from the marginal sea to the general circulation via a streamtube Price and Baringer type of model (as done for example in Price and Yang (1998)). In collaboration with scientists from the modeling centers, the WHOI postdoc will explore the relative advantages and disadvantages of the various Z-coordinate approaches to representing entraining gravity currents, and devise improved strategies that better exhibit the physical constraints identified in stage 2. This development will be facilitated by annual visits of the postdoc to the modeling centers, in addition to the annual workshops. The WHOI postdoc will not run GCMs with new parameterizations - that will be left to the modeling centers in Stage 4 - but will rather examine the z-coordinate discretization in idealized frameworks.

Stage 4: Implementation and evaluation of new and existing parameterizations in large-scale models Critical to incorporation of parameterizations in climate models is the thorough evaluation of new and existing parameterizations. We will adopt a systematic three-fold strategy for this purpose, comparing parameterized flows: (i) against several well-observed oceanic overflows; (ii) against a high-resolution "truth" simulations in a suite of idealized simulations; and (iii) in global climate simulations. The first two sets of simulations [(i) and (ii)] will use resolutions typical of the highest resolution current global models (50 km horizontal res. - i.e. a 1deg model at 63degN) and of the highest resolution models that will be used for climate work in perhaps a decade (10 km horizontal res.) but are now used only for limited-duration studies. The global assessments (iii) will be in the 1deg ocean models currently used at GFDL and NCAR for climate studies. This strategy will establish that the parameterizations are faithful to the observed behavior of the ocean, that it is robust across an appropriate range of parameter space, and that it has only net positive effects on the global circulation.

(i) Comparison against observations Here we will use regional simulations of the well-observed overflows in which co-PIs and active collaborators have worked extensively. These include the Red Sea overflow, the Denmark Straits overflow, the Faroe Bank Channel and the Antarctic overflows, as documented above, and earlier studies of the Mediterranean Outflow (Price et al 1993). Together this suite of 5 regional overflows will do much to identify the most successful parameterizations of gravity current entrainment.

(ii) Comparison with high-resolution idealized simulations As a part of the DOME project (without central funding), several of the P.I.s developed a suite of 7 idealized limited area overflow simulations. These can be implemented fairly simply in all of the models to be used here, and by varying the bottom slope, ambient stratification, density contrast of the overflow to the ambient water, and the presence of rotation will evaluate the robustness of parameterizations across a range of parameter space. While this is clearly not an exhaustive set, it should be enough to document whether the parameterizations exhibit acceptable behavior in a broad variety of conditions. A passive tracer introduced into the overflow will allow us to use downstream density-tracer histograms to evaluate the extent to which the parameterizations are correctly capturing the extent and rate of entrainment in a way that is easily applied to all of the models. Once set up, the entire suite of simulations can be done in a few hours. High resolution nonhydrostatic studies (currently being carried out by Legg and Girton) will be used to help determine the behavior that is likely most realistic, as will qualitative comparisons against fluid laboratory studies by our active collaborators Cenedese and Whitehead at WHOI.

(iii) Global climate simulations The impact on global climate simulations is, of course, critical for evaluating the efficacy of the parameterizations of gravity currents. GFDL and NCAR will test promising parameterizations in their climate models, initially for a few years (to examine the local effects of the parameterizations), but eventually for several decades to explore the global effects on the circulation, heat transport and watermass structure. The most promising approaches will be eagerly adopted in the global coupled climate models using GFDL-HIM or GFDL-MOM and CCSM-POP (as appropriate), providing an ultimate, high profile and high intensity evaluation.

When testing overflow parameterizations all the usual parameterizations used in models at climate resolution will also be used - for example, for non-eddy resolving z-grid models the Gent-McWilliams parameterization (Gent and McWilliams, 1990) will be used, and not horizontal diffusion. An important consideration is the behavior of Gent-McWilliams adjacent to the bottom boundary - this is in many ways related to the issue of combining Gent-McWilliams with the surface mixed layer processes, and we anticipate some exchange with researchers involved in the proposed Eddy-Mixed layer interaction CPT on this issue.

Important questions which will be considered in this evaluation phase are: How sensitive are the density currents to differences in entrainment parameterizations? How accurate must these parameterizations be in order to adequately capture the general behavior of overflows; will some approximate estimates work fine, or will small changes induce drastically different behavior?

The implementation and evaluation of new parameterizations will be greatly facilitated by sharing of efforts within this team. For example, we expect that efforts to implement a new parameterization in one of the isopycnal/hybrid coordinate models (e.g. HYCOM, HIM, POSEIDON) will be readily exploitable by the others in this class. Since more extensive, and therefore time-consuming changes will be needed in z-coordinate models (e.g. CCSM-POP, GFDL-MOM, MITgcm), the parameterizations that require extensive changes to the structure of the ocean model (e.g. Killworth and Edwards, 1999) will first be implemented at either GFDL or NCAR, with evaluation at the other center following from promising results. Via its new hire, GFDL will take the lead in implementing Killworth and Edwards, while NCAR will do the same for the Price and Yang (1998) approach. In this way, this well-coordinated team will enable us to evaluate a broader range of ideas and avoid redundant exploratory efforts within the group.

This evaluation effort will begin immediately for existing parameterizations, and incorporate new parameterizations whenever they are made available from Stage 3. This component of the project will involve effort from most of the team. The GCM numerical model integrations will be carried out by the teams from the modeling centers (GFDL-MOM, GFDL-HIM and CCSM-POP), the Miami postdoc (HYCOM, under supervision from Ozgokmen and Chassignet) and Schopf (POSEIDON). For (i) (comparison with observations) the observationalists in the team (Price, Gordon, Peters) and active collaborators, will participate in sharing necessary data and insight for model initialization and assessment. For (ii) (idealized calculations) the process modelers (Legg and Ozgokmen) will provide high-resolution numerical simulations for comparison. Ezer will provide a comparison with the sigma-coordinate Princeton Ocean Model which includes the Mellor-Yamada turbulence closure scheme to represent mixing, allowing a further assessment of the influence of vertical coordinate on overflow processes and the ability of turbulence closure models to represent the overflow mixing and entrainment processes (following from Ezer and Mellor, 2003). The sigma-coordinate expertise will also provide valuable guidance in designing appended bottom boundary layer parameterizations (such as Killworth and Edwards) for use in Z-coordinate models. Part (iii) (global climate simulations) will be carried out by the modeling centers only.

Ongoing results from this stage of the study will be communicated at the second and third workshops (which will probably focus on comparison of existing parameterizations, and evaluation of new parameterizations, respectively). These workshops will also form a forum for evaluation of the model/data intercomparison, and for dissemination of the assessment to other modeling groups (e.g. MITgcm).

Stage 5: Assessment of poorly understood processes where more observations/studies are needed: This final stage is intended to form the lead into future work, and will form the focus of the final workshop, to which again a large community of researchers will be invited. It is likely that the model development/assessment will suggest many new questions. A successfully implemented CPT will not imply that we fully understand gravity currents, but only that we have made progress in converting current understanding into model parameterizations. Model parameterization schemes may involve constants whose values are poorly known. At the final workshop we will discuss field experiments and process studies which might help to clarify remaining areas of uncertainty and refine the models further.

4. Team responsibilities and management plan

A central component of our plan is a large annual workshop, to which our active collaborators, and others will be invited. JOSS (UCAR) will make the logistical arrangements necessary for such a workshop. UCAR will submit a separate proposal for the 3 annual workshops, totaling approximately \$53K per year, assuming 30 attendees for a workshop in the Boulder area. Workshops will be coordinated with those of other CPTs.

The other central component of our plan is 2 postdocs, one at WHOI and one at Miami, a new term employee at GFDL, and substantial effort from existing staff at both NCAR and GFDL. NCAR and GFDL teams will also apply for substantial inhouse computing resources. The PIs who are outside the modeling centers have requested only modest levels of support from this grant, typically 1 man month per year. This is sufficient to support their travel to workshops and to facilitate their collaboration with CPT colleagues. In most cases these PIs will be receiving the majority of their salary support from ongoing, related grants, and will be requesting future support for research related to the science objectives discussed here. In this sense we regard the CPT as a vehicle for coordination and collaboration of ongoing and future gravity current related work.

Legg will be coordinating PI for the project, and will be responsible for the scientific arrangements for workshops (logistics handled by JOSS), and establishment of a webpage and bulletin board. Legg, Yang and Price will supervise the WHOI postdoc, who will concentrate on Stage 3, the development of new parameterizations, and their implementation in a z-coordinate discretization, with collaboration from GCM modelers. Price, Gordon and Peters will provide input from the observations, both in Stage (1 and 2), and for the GCM model verification (stage 4). Ozgokmen and Legg with significant input from active collaborators will perform the evaluation of entrainment in process studies for stage 2, with additional calculations if needed and if the level of support allows. The Miami postdoc, under supervision from Chassignet and Ozgokmen will implement parameterization schemes in HYCOM, and carry out regional and basin-scale assessments of the overflow representation, focusing on the Denmark Straits, as well as the idealized scenarios detailed in Stage 4(ii). The Miami postdoc will collaborate with Shan Sun (NASA/GISS) to evaluate the parameterization in coupled simulations using the GISS/HYCOM coupled models. Ezer will carry out idealized simulations with POM as for Stage 4(ii).

The modeling center teams at GFDL and NCAR will share the burden of implementing and assessing proposed Z-coordinate approaches (Stage 3 and 4) in close consultation, with participation from the WHOI postdoc. At NCAR, Danabasoglu and Large will oversee assessments and changes in the ocean component of the CCSM climate model, both uncoupled and fully coupled. Byran will become involved at a later stage, and focus on the behavior of emerging schemes at higher (eddy resolving) resolution. Griffies and Hallberg will supervise and participate in the inclusion and evaluation of parameterizations (Stages 3 and 4) in MOM by the new GFDL Federal Term Employee. Hallberg will take the lead in HIM assessments of refined isopycnal model parameterizations proposed by the team (Stages 3 and 4), with some assistance from the GFDL Term Employee, and in consultation with the Miami group.

5. Timeline

Year 1: Stages 1 and 2, evaluation of entrainment and its dependences in existing observations and process studies, to culminate in 1st workshop. Stage 4, implementation and evaluation of parameterization schemes in GCMs, for existing parameterizations, focusing on regional and idealized cases. Beginning of Stage 3, examination and extension of existing parameterization schemes.
Milestones: Characterization of entrainment in existing observations and process studies completed. Regional and idealized scenario comparison of GCMs with existing parameterizations completed.

Year 2: Stages 1 and 2 continue for new process studies/observations. Stage 4 continues, focusing on global climate simulations with existing parameterizations. Stage 4 comparison with observations continues. Stage 3 continues, and new parameterization schemes begin to be incorporated into GCMs, with assessment focusing on regional and idealized studies. 2nd workshop focuses on GCM assessment of existing parameterization schemes, comparison with data, and new developments in parameterization schemes.
Milestones GCM comparison of global climate simulations with existing parameterizations completed. Simplified conceptual models with improved entrainment representation completed.
Year 3: Stages 3 and 4 continue, focusing on implementation of new schemes in models, and assessment in global simulations. Results from any new observations/process studies are incorporatedinto stage 3. Final workshop focuses on new parameterization schemes and their impact on climate simulations, and future directions.
Milestones Implementation of new parameterizations in GCMs completed. Assessment of new parameterizations in regional, idealized and global climate scenarios completed.

6. Collaborators

In addition to the PIs, many other researchers have expressed an interest in sharing data, communicating results from ongoing work, and attending workshops. These include: Amy Bower, Claudia Cenedese, Jack Whitehead, Larry Pratt, Karl Helfrich, James Girton, Mary-Louise Timmermans, Mike McCartney (all WHOI); Vitalii Sheremet, Georgi Sutyrin, Dave Hebert, Tom Rossby, Mike

Prater (all URI); Alistair Adcroft (MIT), David Adamec (NASA-GSFC), Shan Sun (NASA-GISS), Rainer Bleck (LANL), Andreas Thurnherr (FSU), Bill Johns (Miami), Geno Pawlak (Hawaii), Bill Smyth (OSU), Larry Armi (SIO).