MARGINAL SEA OVERFLOWS FOR CLIMATE SIMULATIONS

J. F. PRICE AND J. YANG
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts, 02543, USA

Abstract

This note describes a very simple parameterization of water mass transformation by marginal seas. This parameterization attempts to collapse marginal sea processes into a sidewall boundary condition suitable for an OGCM. Exchange dynamics are treated by hydraulic control models, and descent and mixing are treated by a model of a rotating, entraining density current. This parameterization has been tested by comparison to some well-measured overflows, and it has been implemented in a z-level OGCM to see what effects marginal sea processes have on the deep circulation of an Atlantic-sized basin. Compared to an OGCM solution without a marginal sea, but one which still has a vigorous thermohaline circulation, the combined model solution has much better deep water properties and a rather different circulation in the northern basin.

1. Water Mass Transformation by Marginal Seas

The source waters of the deep circulation can be traced to a few marginal seas that produce a distinctive, dense water type by virtue of their restricted exchange with the open ocean (Whitehead *et al.*, 1974; Warren, 1981). In the present climate, the most important sources of deep water are two overflows from the Nordic Seas — one through Denmark Strait and another through Faroe Bank Channel (Dickson *et al.*, 1990; Borenäs and Lundberg, 1988) — and from the marginal seas and shelf regions surrounding the Antarctic continent (principally the southern Weddell Sea and the Ross Sea; Foldvik *et al.*, 1985). These marginal seas serve as concentration basins (Stommel and Bryden, 1984) that take in oceanic surface water and convert it to a much denser source water that is returned as an overflow. Several important intermediate water types are produced in a similar way. The effects of marginal sea overflows are thus imprinted directly onto the water mass properties and the circulation of the deep ocean (Reid and Lynn, 1971).

For some purposes, e.g., decadal simulation of the present North Atlantic circulation (DYNAMO, 1997), it may suffice to specify the important marginal sea overflows at their present values and then leave them fixed. For climate simulations, and especially those involving a time-changing deep ocean (e.g., Duplessey *et al.,* 1988), it seems essential to represent water mass transformation by marginal seas in a physically consistent and plausible way. This presents a considerable challenge.

Overflows are bottom-trapped density currents, and are thus strongly affected by bottom topography. They have small vertical scales, being typically about 100 - 200 m thick (Figure 1), and they have horizontal scales (width) of from 10 to several hundred kilometers. Their explicit representation would thus require much greater vertical and horizontal resolution than is otherwise desirable in climate models. As they descend the continental slope, overflows may mix intensely with oceanic water, typically doubling their initial volume transport (Smith, 1975; Price and Baringer, 1994). As a consequence of these small spatial scales and energetic mixing dynamics, realistic marginal sea overflows do not arise spontaneously in climate-scale OGCMs.

Here we report on an ongoing effort to make a very simple parameterization of the water mass transformation process by marginal seas. From an oceanic perspective, this process occurs in a small region near the connecting strait, roughly within one grid cell of a large-scale OGCM. Thus it seems appropriate to collapse the process into a sidewall boundary condition on an OGCM, and the present version is called the Marginal Sea Boundary Condition, or MSBC. The MSBC is built from coupled models of marginal sea/ocean exchange, and descent and entrainment of a density current (Section 2) (see Speer and Tziperman, 1990, for a similar approach). Although the MSBC is not completely satisfactory in its present form (some tests are in Section 3), we have nevertheless begun to examine what consequences an explicit representation of marginal sea processes might have on the deep ocean climate and circulation of an idealized Atlantic-size basin (Section 4). In closing (Section 5), we indicate a few of the many areas where this parameterization could be improved, and we also consider other possibilities for the marginal sea problem.

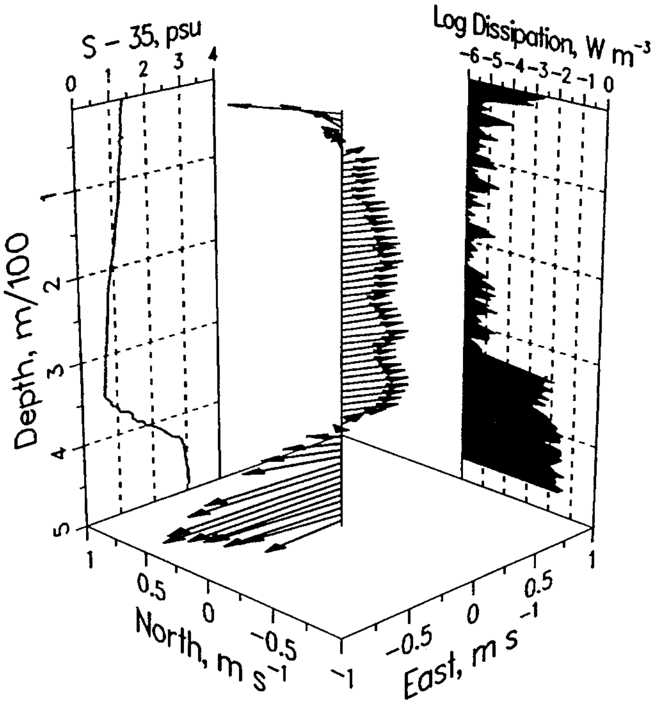

Figure 1. Profiles of salinity, horizontal current, and turbulent dissipation measured near the center of the Mediterranean overflow and just seaward of the shelf-slope break in the Eastern Gulf of Cádiz (from Price *et al.* 1993). The view is toward the northeast. Saline Mediterranean overflow water was flowing westward into the Gulf of Cádiz while the overlying North Atlantic Central water was flowing eastward into the Mediterranean Sea. The dissipation measured within the overflow was about four orders of magnitude larger than in the Atlantic water (which has dissipation values typical of the mid-ocean thermocline). Inferred bottom stress was about 3 Pa, and there was intense vertical mixing between the Mediterranean overflow water and Atlantic water.

2. A Marginal Sea Boundary Condition

The process of water mass transformation by a marginal sea is imagined to occur in four steps (Figure 2):

First, there must be a buoyancy loss to the atmosphere over the marginal sea. The heat and fresh water flux over the marginal sea are presumed given either from a climatology, as in the test cases described below, or in some future version by an atmospheric GCM. The marginal sea is modeled as a single box having uniform and steady properties.

Second, the dense 'source' water fills the marginal sea up to the depth of the sill within the strait connecting the marginal sea to the open ocean, and overflows steadily into the open ocean. This sets up a two-way exchange

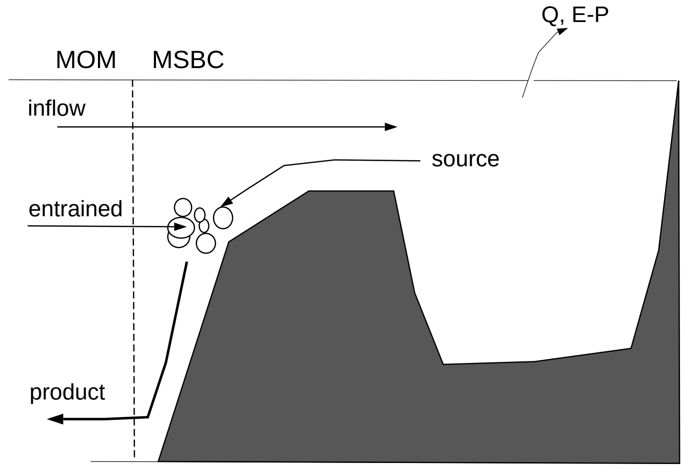

Figure 2. A schematic of the water mass transformation process envisioned to occur in marginal seas that produce deep or intermediate waters. The dashed vertical line at left is the sidewall boundary of an OGCM (the Modular Ocean Model, MOM, in this study) through which the MSBC withdraws, modifies, and reinjects water. The OGCM is unaware of the source water *per se*.

flow in which the volume transport of overflowing source water, M_s, is compensated by a nearly equal 'inflow' of oceanic water, M_i, where M is a volume transport. The properties of the inflowing oceanic water are given from climatology in the test cases below, or from the OGCM. The volume, heat, and salt balances for the marginal sea are then

$$M_s + M_i = (E - P)A, \tag{1}$$

$$T_s M_s + T_i M_i = QA/(\rho C_p), \tag{2}$$

$$S_s M_s + S_i M_i = S_s(E - P)A, \tag{3}$$

where A is the surface area of the marginal sea subject to the heat and fresh water fluxes Q and $E-P$. In practice the net freshwater flux through the sea surface is much less than the exchange terms, and to avoid having to treat a barotropic flow through the boundary, the approximation $M_s = -M_i$ is made in the volume budget implemented in the numerical model (Section 4).

To calculate the magnitude of the exchange, M_s, we have used hydraulic models of density-driven exchange. If the strait is narrow compared to the radius of deformation and if the surface inflow has speeds comparable to that of the overflow (as in the Mediterranean overflow through the Strait of Gibraltar), then we use the Bryden and Stommel (1984) model updated by Bryden and Kinder (1991),

$$M_s = 0.07 g'^{1/2} d^{3/2} W, \tag{4}$$

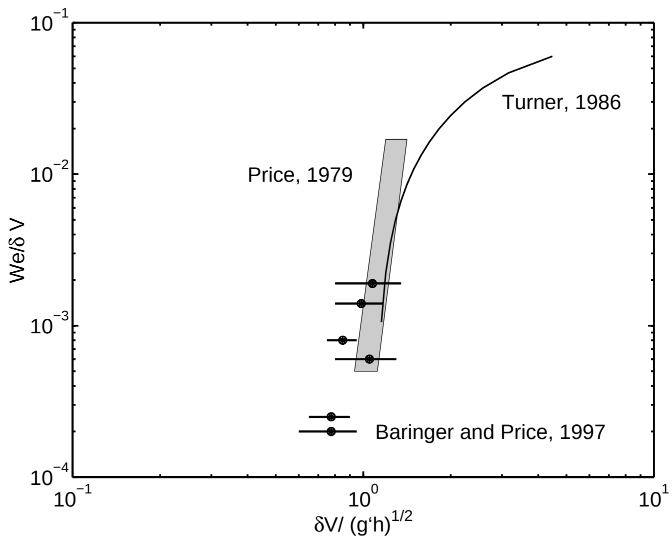

Figure 3. Observed entrainment rate, W_e, normalized by the velocity difference δV, and plotted against the internal Froude number. Data are from laboratory experiments analyzed by Price (1979) (the shaded rectangle), from laboratory experiments analyzed by Turner (1986) (the thin solid line), and from estimates of the Mediterranean overflow in the eastern Gulf of Cádiz by Baringer and Price (1997a,b) (the six discrete points that represent averages across the overflow). The last-named data are evidently the only such oceanic estimates, and it is encouraging (for laboratory studies) that they appear to be consistent with the laboratory-derived estimates.

where $g' = g(\rho_s - \rho_i)$ is the buoyancy anomaly of the source water with respect to the adjacent oceanic water, d is the sill depth, and W is the width of the strait. If the strait is wider than the radius of deformation and if the inflow is not geometrically constrained (as in the Nordic Sea exchange with the North Atlantic), then we use the Whitehead *et al.* (1974) model for maximal geostrophic flow through a strait,

$$M_s = \frac{g' h_u^2}{2f}, \tag{5}$$

where f is the usual Coriolis parameter, and h_u is the thickness of the source water layer above sill depth (more on this below). The oceanic inflow is not explicit in this one-layer exchange theory, but we have assumed that the volume budget (1) still holds.

Third, the overflow forms a density-driven bottom current which descends the continental shelf and slope as it flows into the open ocean. Along the way, most marginal sea overflows double or triple their volume transport by entraining oceanic water which will generally have a considerably different temperature and salinity. Entrainment thus causes a substantial

case	latitude	A, 10^6 km^2	Q, W m^{-2}	E-P, m yr^{-1}
Mediterranean	36	2.5	0	0.7
Denmark Strait	62	3.0	-30	-0.08
Nordic Sea	62	3.0	-60	-0.15

TABLE 1. Some relevant external variables for simulation of the Mediterranean Sea, Denmark Strait, and combined Nordic Sea overflows. Area is ice-free area, Q is the annual average heat flux (negative indicates heat loss from the marginal sea) (from Bunker, 1980), and E-P is the evaporation minus precipitation (positive indicates excess evaporation) (after Bryden and Kinder, 1991, and Peixoto and Oort, 1992). For the Denmark Strait case the Q and E-P are reduced by half from their full values in order to give reasonable heat and salt flux through Denmark Strait alone.

change of the overflow properties. To model the entrainment process, we use the end point model of an entraining, rotating density current developed by Price and Baringer (1994). This model assumes that entrainment occurs in a localized region just over the shelf-slope break and that it depends upon an internal Froude number of the overflow (Figure 3). The entrained oceanic water is taken to be the oceanic water at the depth of the shelf-slope break ('entrained' in Figure 2). The product water properties are then

$$M_p = M_s \frac{1}{1-\Phi}, \tag{6}$$

$$T_p = T_s - (T_s - T_e)\Phi, \tag{7}$$

$$S_p = S_s - (S_s - S_e)\Phi, \tag{8}$$

where the entrainment parameter

$$\Phi = 1 - F_{geo}^{-2/3} \tag{9}$$

depends upon the geostrophic Froude number, $F_{geo} = U_{geo}/\sqrt{g' h_{geo}}$, evaluated at the shelf-slope break. The geostrophic speed, $U_{geo} = g'\alpha/f$, where α is the slope of the continental slope, and the thickness, h_{geo}, depends upon the spreading of the overflow from the strait to the shelf-slope break (further details are in Price and Baringer, 1994).

Fourth, the mixed overflow water, called 'product' water, is presumed to descend the continental slope without further mixing. This product water is the net result of the water mass transformation process and is a named water type, e.g, Mediterranean Water, and Eastern and Western North Atlantic Deep Water from the Nordic Sea overflows through Faroe Bank

case	d, m	h_u, m	W, km	slope	depth ssb, m
Mediterranean	300	-	20	0.012	400
Denmark Strait	600	400	40	0.028	1000
Nordic Sea	700	500	50	0.028	1000

TABLE 2. External variables continued. d is sill depth, W is strait width (for the Mediterranean case, at the surface), h_u is the thickness of the source water within the marginal sea (not required for the Mediterranean), width is strait width, slope is the bottom slope seaward of the shelf-slope break, and depth ssb is the depth of the shelf-slope break.

Channel and the Denmark Strait. The product water is passed over to the OGCM at the depth where it is either equilibrated in the mid water column or settled onto the bottom as a density current. This last step can be problematic; in some cases where the product settles at mid-depth (e.g., the Mediterranean), we have found that the OGCM may be unable to carry the product water away from the boundary at a sufficient rate, with the result being a literal (and then a figurative) blowup within the OGCM thermocline. In the cases shown in Section 4, the product water is dense enough to reach the sea floor and can readily advect away as a density current.

3. Some Tests and Experiments

3.1. THE MEDITERRANEAN OVERFLOW

This scheme has been tested by comparison to observations of the Mediterranean overflow through the Strait of Gibraltar, which is the best-observed and most intensively analyzed overflow (Ambar and Howe, 1979; Armi and Farmer, 1988; Bryden and Kinder, 1991; Ochoa and Bray, 1991; Baringer and Price, 1997a,b). External parameters needed to run the MSBC in a stand-alone mode are in Tables 1 and 2; the inflow and entrained water properties were taken from observations in the western Gulf of Cádiz.

The Mediterranean case goes through readily (Table 3), and the MSBC gives transports and T/S predictions of the source and product waters that are reasonable compared to observed values. In particular, the product water is predicted to have a salinity of about 36.5 and a transport of a little more than 3 Sv, both of which compare well to the observed Mediterranean overflow in the western Gulf of Cádiz (Ochoa and Bray, 1991).

variable	mid-depth, m	T, C	S	density, sigma	M, Sv
inflow	70	14.58	36.25	27.03	-.9
source	190	14.58	38.62	28.87	.9
entrained	400	12.10	35.70	27.11	-2.6
product	915	12.74	36.46	27.58	3.5

TABLE 3. A simulation of the Mediterranean overflow by MSBC. Inflow is surface oceanic water that flows into the marginal sea (properties taken from an observed profile), source is the source water that overflows from the marginal sea, entrained is the oceanic water entrained into the overflow (properties from an observed profile), and product is the equilibrated product water that is passed to the OGCM. mid-depth is the mid-depth of the layer, density is potential density, and positive transports are directed into the OGCM.

3.2. THE NORDIC SEA OVERFLOWS

The MSBC has also been tested against observations of the Nordic Sea overflows, which are more interesting (problematic) on several counts. The transport and water mass properties of these overflows are well known (Warren, 1981; Swift, 1984; Dickson *et al.*, 1990; Saunders, 1990), though the exchange and mixing dynamics have not been studied intensively and appear to be quite complex. There are two major overflows from the Nordic Seas, one through Denmark Strait and one through Faroe Bank Channel, and there is a significant exchange with the Arctic Ocean through Fram Strait. Thus the heat and salt budgets for the Nordic Sea are not closed using the overflows only. We will nevertheless attempt both a combined Nordic Sea overflow simulation, as we will describe in a moment, and a Denmark Strait case separately since the oceanic conditions are somewhat different for the two overflows. To run the Denmark Strait case, the air/sea fluxes were reduced by half from their nominal values on the assumption that about half the total Nordic Sea overflow comes through Denmark Strait (Table 1). This gives a reasonable density contrast between the source and oceanic waters, about 0.5 kg m^{-3}, and thus makes a useful test of the exchange and entrainment pieces of the MSBC.

The estimated exchange through Denmark Strait is reasonable, $\approx$2.9 Sv, as are the source and product water properties. However, to obtain this result we had to insert an additional key piece of information, namely that the upstream thickness of the source water layer was less than the sill depth by 200 m (the h_u of Table 2; Whitehead, 1995). This is a fair approximation of the actual stratification in the Nordic Sea, and had we not done this, i.e., had we applied the box model approximation consistently,

variable	mid-depth, m	T, C	S	density, sigma	M, Sv
inflow	150	6.4	34.98	27.48	-2.9
source	550	-0.3	34.89	27.93	2.9
entrained	1000	4.1	34.91	27.71	-2.1
product	4000	1.5	34.90	27.93	5.0

TABLE 4. A (partial) simulation of the Denmark Strait overflow. The product water was predicted to reach the sea floor at 4000 m depth.

then the exchange theory would have given too much transport by about a factor of two (also see Saunders, 1990; Killworth, 1994; Whitehead, 1995). This important effect of the marginal sea stratification could perhaps be computed in a future version of this model that includes a resolved marginal sea. For now it must be taken from observations, which leaves this result less than fully predictive.

3.3. A COMBINED, COUPLED NORDIC OVERLOW

In the so-called Nordic Sea overflow case, the MSBC was configured to represent the combined Denmark Strait and Faroe Bank Channel overflows (Tables 1 and 2), and the air/sea fluxes were set to their full values. The MSBC was fully coupled to the northern end of a square, Atlantic-sized basin represented by the Modular Ocean Model, MOM. Inflow and entrained water properties were taken from the northern end of the ocean basin (and the h_u from above was retained). The result was a considerably stronger overflow, having a product water transport of $\sim$11.4 Sv (Table 5), of which about half came from entrainment. This product water transport is about 10% greater than the southward flow of North Atlantic Deep Water (NADW) observed along the eastern continental slope of Greenland (Dickson *et al.*, 1990). The temperature, salinity, and density of the product water (2.2^{o}C, 34.93, and 27.90 kg m^{-3}) are reasonable as an average of newly formed NADW, but note that the present MSBC is unable to give an estimate of the considerable range of temperature and salinity within the real NADW.

3.4. SENSITIVITY TO SURFACE FLUXES

The MSBC development would be otiose if it reproduced only known cases. Its value is that it can make definite (and provocative, we hope) predictions of the change in marginal sea overflows that might occur as part of a climate change scenario. A straightforward example to consider is the effect of an

variable	mid-depth, m	T, C	S	density, sigma	M, Sv
inflow	150	6.3	34.96	27.48	-5.9
source	650	-1.7	34.86	28.06	5.9
entrained	1000	6.3	34.96	27.48	-5.5
product	4000	2.2	34.93	27.90	11.4

TABLE 5. Output from a simulation of the combined Nordic Sea overflow implemented in MOM. In this case the inflow and entrained water properties came from the northern boundary of MOM.

increased (but steady) E-P over the Mediterranean basin (and holding all other external variables fixed at their nominal values). The salinity and the transport of the source water both increase with an increased E-P, and in a comparable way (Figure 4). This change in source water properties is directly attributable to the Stommel and Bryden (1984) exchange dynamics. The source water then must go through the descent and entrainment step before it creates the mixed product water that reaches the open ocean. The MSBC predicts that the transport of product water will be increased substantially while the salinity will remain almost unchanged. This is a direct consequence of the entrainment formulation of Price and Baringer (1994). The upshot is that for all but a very large decrease of E-P from present values, the Mediterranean overflow is predicted to respond to changed E-P with a changed transport of product water having a nearly constant salinity. A rather similar result comes from changing the heat flux over the Nordic Sea (Figure 5).

Are these results realistic? We are not aware of an empirical basis upon which they can be judged (a point we will return to at the end).

4. Does It Matter How or Whether We Treat Marginal Seas?

To see whether an explicit treatment of marginal seas makes a difference in climate-scale simulations, we have run some twin experiments in which the ocean is a square Atlantic-size basin represented by MOM. The surface boundary conditions were restored to averaged T/S, and there was an applied wind stress. Over a small strip on the northern edge of the basin, the boundary conditions were an imposed heat flux and fresh water flux; these were either spread over an open ocean domain, in which case we will call it the ocean-only model, or absorbed by the MSBC configured to represent the combined Nordic Sea overflow. (For a different take on this question, see Gerdes and Koberle, 1995, and also Roberts and Wood, 1997)

The ocean-only model makes a vigorous thermohaline circulation (THC)

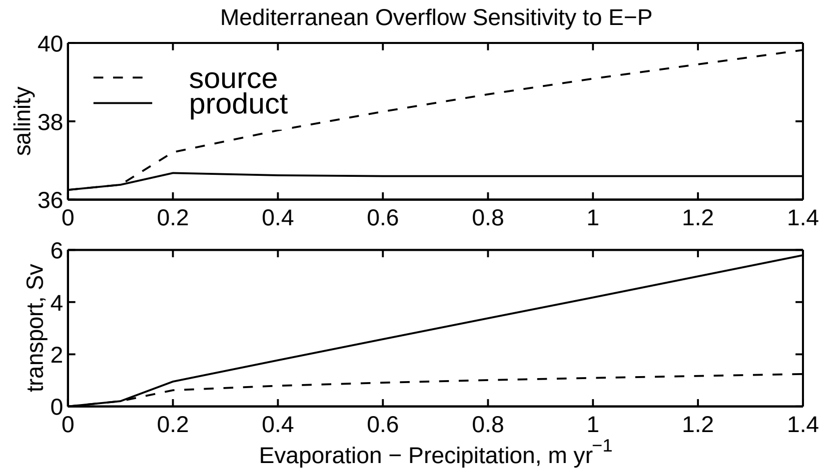

Figure 4. The MSBC simulation of the Mediterranean overflow as a function of E-P over the Mediterranean basin. The upper curves are the salinities of the source water (dashed line) and the product water (solid line). The lower set of curves are the transports. Note that for small changes of E-P about the present value ($\approx$ 0.7 m yr^{-1}), the result is a nearly constant product water salinity, though with a changed transport.

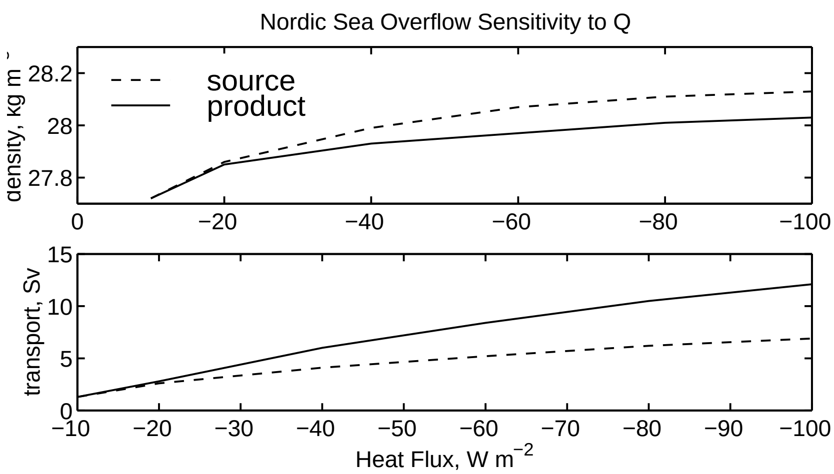

Figure 5. The MSBC simulation of the combined Nordic overflow as a function of heat flux over the basin. The upper curves are the densities of the source water (dashed line) and product water (solid line). The lower set of curves are the corresponding transports. As before, the largest changes appear to be in the transport rather than in the density of the product water (though even rather small changes of density could be important when compared to the density of the southern source water).

driven by deep, open ocean convection. The amplitude of the THC is at least as large as we expect for the true North Atlantic (Figure 6a; the absolute maximum is roughly 25 Sv). With the MSBC present (Figure 6b), the amplitude of the THC in the far field (at the equator, say) is about the same as before, but the absolute maximum is reduced to about 17 Sv. Some significant features of the THC, especially the strength and the direction of the western boundary current, also change with the presence or absence of the MSBC. These changes are due in part to different sources of vorticity, as described further by Yang and Price (1998).

The stratification along the northern boundary is affected markedly by the deep water source (Figure 7). In the ocean-only model, the deep water comes directly from the sea surface by deep convection. The northern end of the ocean is thus very weakly stratified, and the abyssal ocean is much too warm. With the MSBC present, the deep water in the northern basin comes from the marginal sea as a deep overflow, and the concentration basin effect noted at the beginning of this note is evident as a much colder and much more realistic abyssal ocean.

The southern ocean does not have a marginal sea process in these simulations. A shift between mostly northern or mostly southern deep water can thus be fairly pronounced when the MSBC is applied or removed from the northern boundary.

5. Closing Remarks

Two of the obvious shortcomings of the MSBC — the inability to treat time-changing conditions and the need to insert additional information about stratification within the Nordic Sea — stem from the box model approximation of the marginal sea. The box model was adopted purely for convenience, and could be replaced by a resolved marginal sea while still retaining the exchange and entrainment dynamics (which would then be applied on both sides of the ocean/marginal sea boundary).

We are aware of another shortcoming that might not have been apparent since we emphasized bulk properties, e.g., the average temperature and the net transport of the overflows. These bulk properties are, of course, passed consistently from one model stage to the next (i.e., they are conserved). However, real overflows have significant across-stream variability of temperature, salinity and currents (Baringer and Price, 1997a) that should also be matched consistently through the entire model (see Pratt and Smith 1997). This may be of some importance to the ocean climatology and to the dynamics of the deep circulation because overflows are sources not only of heat and volume, as accounted for here, but also of thermal and haline variability and of vorticity.

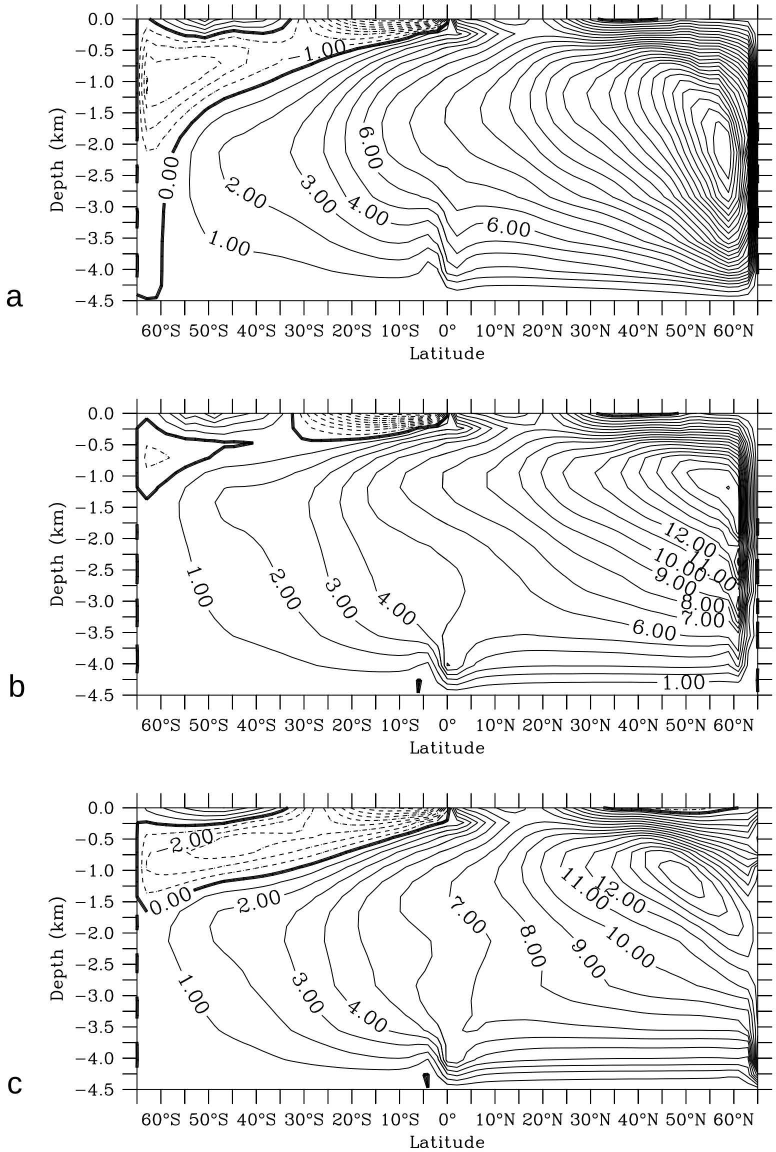

Figure 6. The meridional overturning streamfunction from MOM simulations of an Atlantic size basin. (a) MOM only. (b) MOM with a northern sponge layer that restores the northern boundary T/S toward observed values. (c) MOM with a Nordic Sea-like MSBC. Note that in the latter solution many, but not all, streamlines originate on the northern boundary where there is flow out of the ocean and into the marginal sea at depths above about 1 km, and flow into the ocean at depths greater than about 4 km. The amplitude of the far field THC is little affected by the MSBC, but the distribution of northern/southern source deep water is somewhat altered, as is the deep stratification.

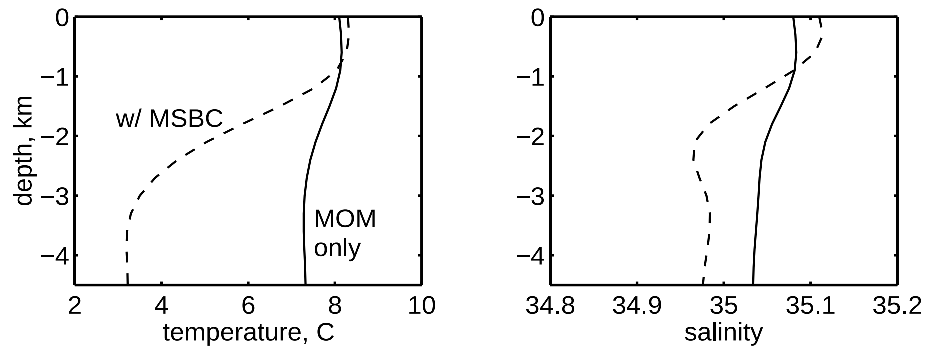

Figure 7. T/S profiles averaged over the northern end of the ocean basin. The solid lines are from MOM only, while dashed lines are from MOM with the MSBC. In the former, deep water comes directly from the sea surface by convection, and hence the northern basin is nearly homogeneous vertically.

An alternative approach to representing overflows in OGCMs is to work toward a model of bottom boundary layer processes that will suffice to treat all bottom currents, including marginal sea overflows (see Beckmann, 1998). This unified approach is sufficiently different from the present patchwork approach that it is difficult to make comparisons, but we will hazard a couple of comments. First of all, a bottom boundary layer model that successfully subsumes overflow dynamics should, of course, be the long range goal. The reason has less to do with marginal sea overflows *per se*, than with related phenomenon — control and mixing at deep passages (Whitehead, 1995) and seasonal deep water production on continental shelves — which such a model could also represent. Exchange dynamics will probably remain as a distinct problem even after bottom boundary layer processes are a settled issue, if only because of the small spatial scales of the connecting straits. Second, it is interesting to consider whether the kind or quality of understanding needed to build and test a unified model is different from that required to build and test a patchwork model. The construction of a patchwork model requires a greater upfront understanding, or at any rate, more explicit information. However, if the goal is to make climate simulations in a parameter regime outside of modern values, and to do so with some confidence, then the level of understanding needed to test a model must be very high regardless of the way the model was built. For example, the MSBC can readily generate predictions of the Mediterranean overflow under conditions of changed E-P over the Mediterranean basin. As is true with many climate predictions, there are no observations able to refute the result directly (Figure 4). In that case the most sensitive contributor to the prediction is the entrainment formulation, Eqs. (6)–(9). We can have confidence in the result only to the extent that the physical processes that cause entrainment in the Mediterranean overflow are understood from observations, and are represented faithfully within the model. A slightly different example arises from the Nordic Sea exchange problem of Section 3.2 where the issue was the geostrophic exchange model, Eq. (5). Progress toward useful models of the thermohaline circulation is likely to be paced as much by our ability to observe and describe the dynamics of the major overflows, especially those in the Antarctic and Nordic Seas, as by our ingenuity at model building.

6. Access and Acknowledgements

At the time of this writing, the marginal sea parameterization is available from the anonymous ftp site: 128.128.29.54, directory pub/oflow. It is also available from J. Price (jprice@whoi.edu).

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