The Kraus-Turner Mixed Layer Model for Isopycnic Coordinates (KTC)

When HYCOM is run with isopycnic vertical coordinates (MICOM mode), the model automatically uses the Kraus-Turner mixed layer model KTC, which is essentially the mixed layer model embedded in MICOM version 2.8. The calculation of entrainment and detrainment rates from the Kraus-Turner TKE balance is well documented in the MICOM literature and is not repeated here. However, it is of interest to document the detrainment algorithm in comparison to the models used with hybrid vertical coordinates (KTA and KTB). Detrainment is simple for hybrid vertical coordinates, but considerable difficulties arise because the mixed layer base is not a vertical coordinate surface. In contrast, the MICOM mixed layer base is a vertical coordinate, but detrainment is difficult because the density of detrained water must match the reference density of the layer into which it is detrained. Although the same TKE balance governs entrainment and detrainment, the performance of the K-T model can differ substantially between the hybrid and isopycnic versions.

The MICOM 2.8 mixed layer detrainment algorithm was significantly modified from the earlier version described in Appendix E of Bleck *et al* (1992). The goal was to ease the numerical process of springtime mixed layer retreat at high latitudes where stabilizing buoyancy flux (TKE suppression) can result primarily from freshwater input, ice melt, and increased rainfall rather than sensible heat input. In the original detrainment algorithm, heat entering the ocean during a single model time step is distributed over a layer of depth L, the Monin-Obukhov length. The old mixed layer of depth h_1 is thereby divided into a new mixed layer of depth L and a slightly cooler fossil mixed layer (FML) of depth $h_1 - L$. The FML is divided again into two sublayers: the lower one cooled until its density matches that of the nearest (in density space) isopycnic layer, and the upper one heated to raise its temperature to that of the new mixed layer. The cooled sublayer is then detrained into the appropriate isopycnic layer while the heated sublayer is added to the new mixed layer, creating the final mixed layer. At this time, the FML ceases to exist as an identifiable layer.

Problems arise with this scheme in near-freezing water where heat redistribution within the FML has little effect on density and on the density of the lower sublayer in particular. Thus if no suitable isopycnic coordinate layer exists to receive the wintertime mixed layer water, the model mixed layer may not retreat at all. This problem prompted the refinement in the detrainment algorithm discussed here.

A seemingly appealing analog to the temperature treatment in the detrainment scheme would be to postulate that incoming fresh water gets distributed over the depth range L, followed by a redistribution of salinity in the FML with the goal of lowering S in the upper sublayer to the new mixed-layer value while using the extra salt to make the lower sublayer denser and thus more easily detrainable. Tests show that polar mixed layer detrainment indeed ceases to be a problem if salinity is treated this way; however, the price to be paid for this is the occasional creation of an artificial salinity maximum in the seasonal thermocline. The strategy adopted here is to allow downward transfer of S in the FML provided the salinity in the upper and lower sublayer remains in the range defined by the old mixed layer and the model layer with which the particular sublayer eventually will merge.

If we denote the three layers involved - the receiving isopycnic layer plus the old and new mixed layers by indices k, 1, and L, respectively, this strategy can be expressed in the form of two constraints on the resulting salinities S_{lo}, S_{up} in the lower and upper sublayers of the FML:

$$S_{lo} \leq \max\left(S_k, S_1\right) \quad (\text{constraint } 1)$$

$$\min\left(S_1, S_L\right) \leq S_{up} \quad (\text{constraint } 2)$$

If the receiving layer is as fresh as, or fresher than, the old mixed layer ($S_k \leq S_1$), constraint 1 prohibits downward salinity transfer in the FML, and detrainment must take place exactly as described in Appendix E of Bleck *et al.* (1992). The same is true if the new mixed layer is saltier than the old one ($S_L \leq S_1$). The subsequent discussion is therefore limited to the case $S_L < S_1 < S_k$.

Setting $S_{lo} = S_k$ and $S_{up} = S_L$ maximizes salinity flux from the perspective of constraints 1 and 2, respectively. The option that yields the smallest salinity flux will be the one that satisfies both constraints. An important side effect of the first option $S_{lo} = S_k$ is that the T, S properties of the lower sublayer exactly match those of the receiving layer. Since detrainment under these circumstances is computationally simple, the detrainment algorithm explores this possibility first. The condition $S_{lo} = S_k$, together with the requirement $T_{up} = T_L$, uniquely determines S_{up}. If the latter value satisfies constraint 2, detrainment is allowed to proceed.

Consider now the case where setting $S_{lo} = S_k$ violates constraint 2. Downward transfer of S in the FML is then controlled by setting $S_{up} = S_L$. The reduced salt flux in this case is unable to make the lower sublayer as saline as the receiving layer. This mismatch again requires use of the detrainment algorithm described in Appendix E of Bleck *et al.* (1992).

Details of the detrainment algorithm are now presented for the case $S_L < S_1 < S_k$. Let T_L, S_L be the T, S values obtained by distributing thermal energy and freshwater input during the preceding time step over depth L; i.e., over the new mixed layer. Using the nomenclature of Appendix E, the procedure starts with an initially homogenous FML of thickness $h_1 - L$ characterized by old mixed layer values T_1, S_1. (Caution: Appendix E uses subscript 1 to denote values already modified by surface fluxes.) Downward transfer of heat and salt across an imaginary interface creates an upper sublayer characterized by T_{up}, S_{up} and a lower sublayer characterized by T_{dn}, S_{dn}. These four values are related to T_1, S_1 through

$$T_1 = \frac{T_{up}(h_1 - L - h) + T_{lo}h}{h_1 - L}, \tag{1}$$

$$S_1 = \frac{S_{up}(h_1 - L - h) + S_{lo}h}{h_1 - L} \tag{2}$$

where h denotes the thickness of the lower sublayer; i.e., the part of the FML to be detrained into receiving layer k.

If the process is governed by constraint 1, we set $T_{lo} = T_k$ and $S_{lo} = S_k$. In addition, we have $T_{up} = T_L$ regardless of which constraint limits salinity transfer in the FML. It then follows from (1) that

$$h = (h_1 - L)\frac{T_{up} - T_1}{T_{up} - T_k} \tag{3}$$

which, if substituted in (2), yields

$$S_{up} = \frac{S_1(h_1 - L) - S_k h}{h_1 - L - h} = S_1 + (S_1 - S_k)\frac{T_{up} - T_1}{T_1 - T_k}. \tag{4}$$

If this value violates constraint 2, a modified version of the detrainment scheme described in Appendix E of Bleck *et al.* (1992) must be invoked. In this case, salinity transfer is maximized by setting $S_{up} = \min(S_1, S_L)$ which, by virtue of (2), leads to

$$S_{lo} = \frac{S_1(h_1 - L) - S_{up}(h_1 - L - h)}{h}. \tag{5}$$

The analogous formula for T_{lo}, based on (1) and the requirement $T_{up} = T_L$, is

$$T_{lo} = \frac{T_1(h_1 - L) - T_L(h_1 - L - h)}{h}. \tag{6}$$

Note that the value of h appearing in (5) and (6) differs from the value in (3), and moreover is unknown at this point. Mixing the lower part of the FML with layer k produces water of salinity

$$S_{new} = \frac{S_{lo}h + S_k h_k}{h + h_k} = \frac{S_{up}h + S_k h_k - (S_{up} - S_1)(h_1 - L)}{h + h_k} \tag{7}$$

and temperature

$$T_{new} = \frac{T_{lo}h + T_k h_k}{h + h_k} = \frac{T_L h + T_k h_k - (T_L - T_1)(h_1 - L)}{h + h_k} \tag{8}$$

In agreement with Appendix E of BRHS, (7) and (8) are of the form

$$T_{new} = \frac{ah + b}{ch + d} \tag{9}$$

and

$$S_{new} = \frac{eh + f}{ch + d}. \tag{10}$$

The problem is to find h such that $\boldsymbol{r}\left(T_{new}, S_{new}\right) = \boldsymbol{r}_k$. Except for the change in the definition of e and f, the procedure outlined in BRHS for finding h remains unchanged.

REFERENCE

Bleck, R., C. Rooth, D. Hu, and L. T. Smith, 1992: Ventilation patterns and mode water formation in a wind- and thermodynamically driven isopycnic coordinate model of the North Atlantic. J. Phys. Oceanogr., 22, 1486-1505.