9. Ocean modelling using TEOS-10

Ocean models treat their salinity and temperature variables as being conservative, with the choice of variables to date being Practical Salinity and potential temperature. Converting ocean models to be TEOS-10 compatible requires several changes. The model's temperature variable needs to

(i) accurately represent the "heat content" per unit mass of seawater and

(ii) to be as conservative as possible under ocean mixing processes.

Conservative Temperature Θ has these properties whereas potential temperature θ does not. Fortunately it is relatively easy to change ocean models to have Conservative Temperature as their temperature variable. With the expression for density being cast in terms of Absolute Salinity S_{A} and Conservative Temperature Θ as $\hat{\rho}\left(S_{\mathrm{A}},\Theta,p\right)$, the interior of an ocean model can be written totally in terms of this one temperature variable, Θ. In the air-sea interaction module of an ocean model the sea-surface-temperature (SST) needs to be evaluated for use in bulk air-sea flux formulae, and this is done by calling the function **gsw_pt_from_CT**. This conversion from Θ to SST needs to done just at the sea surface in the air-sea interaction module.

The current practice in numerical models is to treat salinity as a perfectly conserved quantity in the interior of the ocean. In order to continue this practice the appropriate model salinity variable is Preformed Salinity S_*. Preformed Salinity and Absolute Salinity are related to S_{R} and S_* respectively by Eqns. (A.20.1) and (A.20.2) of the TEOS-10 Manual, repeated here

$$S_* = S_{\mathrm{R}}\left(1 - r_1 R^{\delta}\right), \tag{5}$$

$$S_{\mathrm{A}} = S_*\left(1 + F^{\delta}\right), \tag{6}$$

where

$$R^{\delta} \ldots \frac{\delta S_{\mathrm{A}}^{\mathrm{atlas}}}{S_{\mathrm{R}}^{\mathrm{atlas}}} \quad \text{and} \quad F^{\delta} = \frac{\left[1 + r_1\right] R^{\delta}}{\left(1 - r_1 R^{\delta}\right)} . \tag{7a, b}$$

The Absolute Salinity Anomaly Ratio, $R^{\delta} \ldots \delta S_{\mathrm{A}}^{\mathrm{atlas}} / S_{\mathrm{R}}^{\mathrm{atlas}}$, is the ratio of the values of Absolute Salinity Anomaly and Reference Salinity in the stored hydrographic atlas, and r_1 is taken to be the constant 0.35.

Because Preformed Salinity S_* is designed to be a conservative salinity variable, blind to the effects of biogeochemical processes, its evolution equation is in the conservative form (see appendix A.21 of IOC *et al.* (2010)),

$$\frac{\mathrm{d}\hat{S}_*}{\mathrm{d}t} = \gamma_z \nabla_n \cdot \left(\gamma_z^{-1} K \nabla_n \hat{S}_*\right) + \left(D \frac{\partial \hat{S}_*}{\partial z}\right)_z . \tag{8}$$

Here the over-tilde of $\hat{S}_*$ indicates that this variable is the thickness-weighted average Preformed Salinity, having been averaged between a pair of closely-spaced neutral tangent planes. The material derivative on the left-hand side of Eqn. (8) is with respect to the sum of the Eulerian and quasi-Stokes velocities of height coordinates (equivalent to the description in appendix A.21 of IOC *et al.* (2010) in terms of the thickness-weighted mean horizontal velocity and the mean dianeutral velocity), while the right-hand side of this equation is the standard notation indicating that $\hat{S}_*$ is being diffused along neutral tangent planes with the diffusivity K and in the vertical direction with the diapycnal diffusivity D (and γ_z^{-1} is the average of the reciprocal of the vertical gradient of Neutral Density or locally-referenced potential density). The model is initialized with values of Preformed Salinity using Eqn. (5) based on observations of Practical Salinity and on the interpolated global observed data base of R^{δ}; this is best done by calling **gsw_Sstar_from_SP**.

In order to evaluate density during the running of an ocean model, Absolute Salinity must be evaluated based on the model's primary salinity variable, Preformed Salinity, and Eqn. (6). This can be done by carrying the following evolution equation for F^{δ}

$$\frac{\mathrm{d}F^{\delta}}{\mathrm{d}t} \;=\; \gamma_z \nabla_n \cdot \left(\gamma_z^{-1} K \nabla_n F^{\delta} \right) + \left(D \frac{\partial F^{\delta}}{\partial z} \right)_z + \tau^{-1} \left(F^{\delta\,\mathrm{obs}} - F^{\delta} \right). \tag{9}$$

The model variable F^{δ} (note that $F^{\delta} = S_{\mathrm{A}} / S_{*} - 1$) is initialized based on observations of $R^{\delta} \equiv \delta S_{\mathrm{A}}^{\mathrm{atlas}} \big/ S_{\mathrm{R}}^{\mathrm{atlas}}$ and the use of Eqn. (7b); this is best done by calling **gsw_Fdelta**. Equation (9) shows that F^{δ} is advected and diffused like any other tracer, but in addition, there is a non-conservative source term $\tau^{-1}\left(F^{\delta\,\mathrm{obs}} - F^{\delta}\right)$ which serves to restore the model variable F^{δ} towards the observed value (found from **gsw_Fdelta**) with a restoring time τ that can be chosen to suit particular modeling needs (see the discussion in appendix A.20 of the TEOS-10 Manual, IOC *et al*. (2010)).

In summary, the approach for handling salinity in ocean models suggested in IOC *et al*. (2010) and summarized here carries the evolution Eqns. (8) and (9) for $\hat{S}_{*}$ and F^{δ}, while $\hat{S}_{\mathrm{A}}$ is calculated from these two model variables at each time step according to

$$\hat{S}_{\mathrm{A}} \;=\; \hat{S}_{*}\left(1 + F^{\delta}\right). \tag{10}$$

It is this salinity, $\hat{S}_{\mathrm{A}}$, which is used as the argument for the model's expression for density at each time step of the model.

The Baltic Sea is somewhat of an exception because its compositional variations are not due to biogeochemistry but to anomalous riverine input of dissolved salts which behave conservatively. Preformed Salinity S_{*} in the Baltic is equal to Absolute Salinity S_{A}, which implies that $r_1 = -1$ and $F^{\delta} = 0$ in the Baltic Sea. Hence in the Baltic, an ocean model simply puts $S_{\mathrm{A}} = S_{*}$ and the value of Absolute Salinity Anomaly δS_{A} is immaterial during the running of the model. Of course the values of δS_{A} in the Baltic are important for relating Absolute Salinity and Preformed Salinity to measured values of Practical Salinity there. The discharges (mass fluxes) of river water and of Absolute Salinity should both appear as source terms at the edges of the Baltic Sea in the model.

If an ocean model is to be run for only a short time (perhaps as long as a century) then it may be sufficiently accurate to carry only one salinity variable, namely Absolute Salinity S_{A}. For longer integrations the neglect of the non-conservative biogeochemical source term means that the model's salinity variable S_{A} will depart from reality. A more detailed discussion of these points is available in appendix A.20 of IOC *et al*. (2010). To our knowledge, as of July 2020, no ocean model has adopted this approach; rather they have used only one salinity variable, namely Absolute Salinity S_{A}.

In summary, the changes needed to make ocean models TEOS-10 compatible are

(i) use an equation of state in terms of S_{A} and Θ, $\hat{v}\left(S_{\mathrm{A}}, \Theta, p\right)$, such as the 75-term expression to be found in **gsw_specvol**(SA,CT,p),

(ii) have Conservative Temperature Θ as the model's temperature variable (note that SST needs to be evaluated in the model's air-sea flux module using **gsw_pt_from_CT** at the sea surface only),

(iii) incorporate the effects of the spatially variable seawater composition using the techniques of appendix A.20 of IOC *et al*. (2010) as summarized above,

(iv) restoring boundary conditions for ocean-only models can be imposed on the model variables S_{*} and Θ,

(v) model output salinities and temperatures are best made as Absolute Salinity S_{A} and Conservative Temperature Θ, consistent with the variables which will be published in oceanographic journals.

To our knowledge, as of July 2020, points (iii) and (iv) have not yet been implemented in ocean models. Rather the model's salinity variable is initialized and is interpreted as Absolute Salinity S_{A}, and if a salinity restoring boundary condition is used, it is applied to Absolute Salinity.