Changes to oceanographic practice under TEOS-10

For the past thirty years we have taken the "raw" data of Practical Salinity S_{P} (PSS-78), *in situ* temperature t (now ITS-90) and pressure p and we have used an algorithm to calculate potential temperature θ in order to analyze and publish water-mass characteristics on the $S_{\mathrm{P}} - \theta$ diagram. On this $S_{\mathrm{P}} - \theta$ diagram we have been able to draw curved contours of potential density using EOS-80.

Under TEOS-10 this practice has now changed:- density and potential density (and all types of geostrophic streamfunction including dynamic height anomaly) are now not functions of Practical Salinity S_{P} but rather are functions of Absolute Salinity S_{A}.

TEOS-10 also defines a new temperature variable, Conservative Temperature Θ, which takes the place of potential temperature θ (see section 5 above). Operationally, the calculation of Conservative Temperature Θ as a function of (S_{A}, t, p) under TEOS-10 is no different in principle from the way potential temperature was calculated from (S_{P}, t, p) under EOS-80; in both cases a simple computer algorithm is called. Conservative Temperature Θ has the advantage over θ of more accurately representing the "heat content" of seawater, and is also much closer (by a factor of a hundred) to being a conservative variable than is potential temperature. Heat is exchanged between the ocean and its atmosphere and ice boundaries as a flux of potential enthalpy which is exactly $c_p^0 \equiv 3991.867\,957\,119\,63 \ \mathrm{J\,kg^{-1}\,K^{-1}}$ times the density times the corresponding flux of Θ. The transport of potential enthalpy $c_p^0\Theta$ in the ocean, and in particular across ocean sections, can be regarded as the transport of "heat" irrespective of whether there are non-zero fluxes of mass and/or of salt across such ocean sections (IOC *et al*., 2010).

Under TEOS-10 is not possible to draw isolines of potential density on a $S_{\mathrm{P}} - \theta$ diagram. Rather, because of the spatial variations of seawater composition, a given value of potential density defines an area on the $S_{\mathrm{P}} - \theta$ diagram, not a curved line. Hence for the analysis and publication of ocean data under TEOS-10 we need to change from using the $S_{\mathrm{P}} - \theta$ diagram which was appropriate under EOS-80, to using the $S_{\mathrm{A}} - \Theta$ diagram. It is on this $S_{\mathrm{A}} - \Theta$ diagram that the isolines of potential density can be drawn under TEOS-10.

Density may be calculated from the sum of the Gibbs functions of pure water (IAPWS-09, Feistel (2003)) and of salt (IAPWS-08, Feistel (2008)) using **gsw_rho_CT_exact**(SA,CT,p) or from the 48-term rational function expression **gsw_rho**(SA,CT,p). The errors involved with using the 48-term expression for density are much less than the uncertainty in the effect of seawater composition on density, and are also much less than the uncertainty of the underlying laboratory density data to which the TEOS-10 Gibbs function was fitted (IAPWS-08, Feistel (2008)). This computationally efficient 48-term expression for density is the obvious choice for use in ocean models since it is a function of the model's temperature variable, Conservative Temperature. The highly accurate nature of the 48-term expression means that theoretical studies, observational oceanography and ocean modeling can all be performed using the same equation of state which is conveniently expressed in terms of Conservative Temperature. This eliminates the need to continually transform from Conservative Temperature back to *in situ* temperature in order to calculate density and its derivatives.

These advantages lead us to recommend the 48-term expression for general use by oceanographers, including for observational studies, for ocean modelling and for theoretical studies, thus ensuring consistency between these different branches of oceanography. The GSW Oceanographic Toolbox provides many functions based on this 48-term equation of state, including **gsw_Nsquared**(SA,CT,p) to evaluate the square of the buoyancy frequency, **gsw_enthalpy**(SA,CT,p) to evaluate the specific enthalpy of seawater, and several functions to evaluate various geostrophic streamfunctions. The geostrophic streamfunction to be used for flow in an isobaric surface is **gsw_geo_strf_dyn_height** while that to be used in approximately neutral surfaces (including potential density surfaces, ω-surfaces and

Neutral Density (γ^n) surfaces) is **gsw_geo_strf_isopycnal**. Also, it is this 48-term expression for density that will be the basis for updated algorithms for ω-surfaces (Klocker *et al*. (2010)) and Neutral Density γ^n (Jackett and McDougall (1997)).

In summary, under EOS-80 we have to date used the observed variables $\left(S_\mathrm{P},\, t,\, p\right)$ to first form potential temperature θ and then we have analyzed water masses on the $S_\mathrm{P} - \theta$ diagram, and we have been able to draw curved contours of potential density on this same $S_\mathrm{P} - \theta$ diagram. Under TEOS-10, the observed variables $\left(S_\mathrm{P},\, t,\, p\right)$, together with longitude and latitude, are used to first form Absolute Salinity S_A using **gsw_SA_from_SP**, and then Conservative Temperature Θ is calculated using **gsw_CT_from_t**. Oceanographic water masses are then analyzed on the $S_\mathrm{A} - \Theta$ diagram (using **gsw_SA_CT_plot**), and potential density contours can be drawn on this $S_\mathrm{A} - \Theta$ diagram using **gsw_rho**(SA,CT,p_ref).

The various oceanographic properties that rely on the equation of state have been written in terms of S_A and Θ in the GSW Oceanographic Toolbox, and all of the oceanographic variables in common use (including geostrophic streamfunctions) have been written using the 48-term expression for density to ensure consistency between ocean models, observational studies and theoretical work. The use of many of these functions can be seen by running **gsw_demo**.