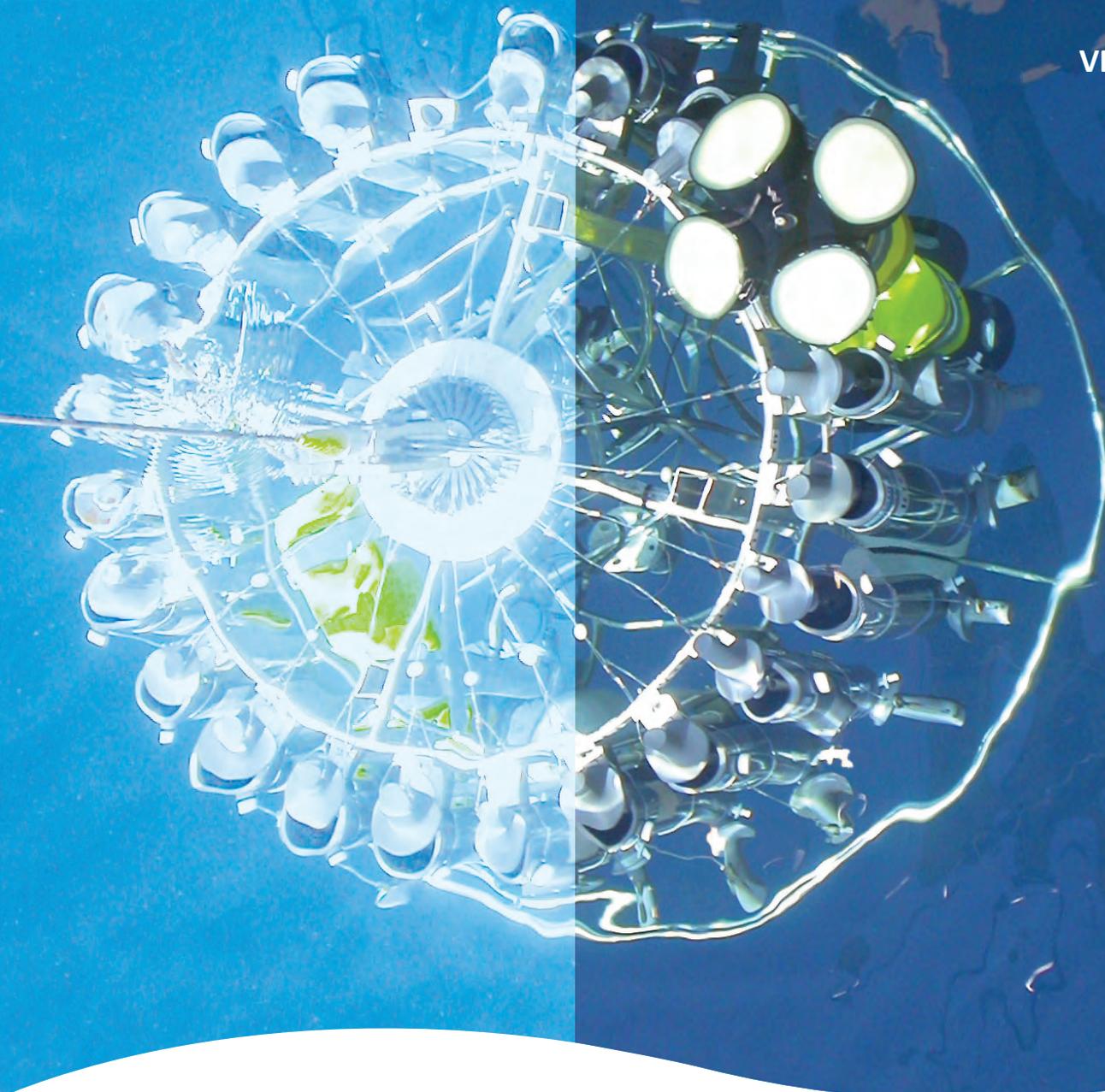


# Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox

VERSION 3.05

May 2015



IOC

The International Thermodynamic Equation Of Seawater – 2010 (TEOS-10) was developed by SCOR/IAPSO Working Group 127 and was adopted by the Intergovernmental Oceanographic Commission (IOC). The members of SCOR/IAPSO Working Group 127 were as follows.

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The photograph on the front cover of a CTD and lowered ADCP hovering just below the sea surface was taken south of Timor from the *Southern Surveyor* in August 2003 by Ann Gronell Thresher. Document cover by Louise Bell.

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# Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox version 3.05

Trevor J. McDougall<sup>1</sup> and Paul M. Barker<sup>1</sup>

May 2011, updated May 2015 with the release of version 3.05

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## 1. Preamble

The International Thermodynamic Equation Of Seawater – 2010 (TEOS-10) allows all the thermodynamic properties of pure water, ice, seawater and moist air to be evaluated in a self-consistent manner. For the first time the effects of the variations in seawater composition around the world ocean are accounted for; these spatial variations of seawater composition cause density differences that are equivalent to ten times the precision of our Practical Salinity measurements at sea.

The GSW Oceanographic Toolbox of TEOS-10 is concerned primarily with the properties of pure liquid water and of seawater; the TEOS-10 software for evaluating the properties of ice and of humid air is available in the SIA (Seawater-Ice-Air) software library from the TEOS-10 web site, <http://www.TEOS-10.org>.

TEOS-10 has introduced several new variables into oceanography, including Absolute Salinity  $S_A$ , Preformed Salinity  $S_*$ , and Conservative Temperature  $\Theta$ . These variables are introduced in this document, and then the use of these variables is discussed, followed by the complete listing and description of the functions available in the GSW toolbox.

Absolute Salinity is the salinity argument of the TEOS-10 algorithms which give the various thermodynamic properties of seawater, and under TEOS-10 Absolute Salinity  $S_A$  is the salinity variable to be used in scientific publications. Note, however, it is Practical Salinity  $S_p$  which must be reported to and stored in national databases. The practice of storing one type of salinity in national databases (Practical Salinity), but using a different type of salinity in publications (Absolute Salinity), is exactly analogous to our present practice with temperature; *in situ* temperature is stored in databases (since it is the measured quantity), but the temperature variable that is used in publications is a calculated quantity, being potential temperature to date, and from now, Conservative Temperature.

For the past thirty years, under EOS-80 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  $\theta$  in order to analyze and publish water-mass characteristics on the  $S_p - \theta$  diagram. On this  $S_p - \theta$  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  $\Theta$ , which takes the place of potential temperature  $\theta$ . Conservative Temperature  $\Theta$  has the advantage over  $\theta$  of more accurately representing the “heat content” of seawater. Under TEOS-10 is not possible to draw isolines of potential density on a  $S_p - \theta$  diagram. Rather, because of the spatial variations of seawater composition, a given value of potential density defines an area on the  $S_p - \theta$  diagram, not a curved line. Hence for the analysis and publication of ocean data under TEOS-10 we need to change from using the  $S_p - \theta$  diagram which was appropriate under EOS-80, to using the  $S_A - \Theta$  diagram. It is on this  $S_A - \Theta$  diagram that the isolines of potential density can be drawn under TEOS-10.

As a fast-track precursor to the rest of this document, we note that these calculations can be performed using the functions of the GSW Oceanographic Toolbox as follows. The observed variables  $(S_p, t, p)$ , together with longitude and latitude, are used to first form Absolute Salinity  $S_A$  using `gsw_SA_from_SP`, and then Conservative Temperature  $\Theta$  is calculated using `gsw_CT_from_t`. Oceanographic water masses are then analyzed on the  $S_A - \Theta$  diagram (for example, by using `gsw_SA_CT_plot`), and potential density contours can be drawn on this  $S_A - \Theta$  diagram using `gsw_rho(SA,CT,p_ref)`.

The more prominent advantages of TEOS-10 compared with EOS-80 are

- For the first time the influence of the spatially varying composition of seawater is systematically taken into account through the use of Absolute Salinity  $S_A$ . In the open ocean, this has a non-trivial effect on the horizontal density gradient, and thereby on ocean velocities and “heat” transports calculated via the “thermal wind” relation.
- The new salinity variable, Absolute Salinity  $S_A$ , is measured in SI units (e.g.  $\text{g kg}^{-1}$ ).
- The Gibbs function approach of TEOS-10 allows the calculation of internal energy, entropy, enthalpy, potential enthalpy and the chemical potentials of seawater as well as the freezing temperature, and the latent heats of melting and of evaporation. These quantities were not available from EOS-80 but are essential for the accurate accounting of “heat” in the ocean and for the consistent and accurate treatment of air-sea and ice-sea heat fluxes in coupled climate models.
- In particular, Conservative Temperature  $\Theta$  accurately represents the “heat content” per unit mass of seawater, and is to be used in place of potential temperature  $\theta$  in oceanography.
- The thermodynamic quantities available from TEOS-10 are totally consistent with each other, while this was not the case with EOS-80.
- A single algorithm for seawater density (the 75-term computationally-efficient expression  $\hat{v}(S_A, \Theta, p)$ ) can now be used for ocean modelling, for observational oceanography, and for theoretical studies. By contrast, for the past 30 years we have used different algorithms for density in ocean modelling and in observational oceanography and inverse modelling.

The present document (McDougall and Barker, 2011) provides a short description of the three new oceanographic variables  $S_A$ ,  $S_*$  and  $\Theta$ , leading into a discussion of the changes to observational oceanography and ocean modelling under TEOS-10 (compared with EOS-80), and then we list and describe the functions in the GSW Oceanographic Toolbox. The present document ends with the recommendations of SCOR/IAPSO Working Group 127, as endorsed by the Intergovernmental Oceanographic Commission, for the nomenclature, symbols and units to be used in physical oceanography, repeated from appendix L of IOC *et al.* (2010). Another document “What every oceanographer needs to know about TEOS-10 (The TEOS-10 Primer)” (Pawlowicz, 2010) provides a succinct introduction to the thermodynamic theory underlying TEOS-10 and is available from [www.TEOS-10.org](http://www.TEOS-10.org).

Note that when referring to the use of TEOS-10, it is the TEOS-10 Manual which should be referenced as IOC *et al.* (2010) [IOC, SCOR and IAPSO, 2010: *The international thermodynamic equation of seawater – 2010: Calculation and use of thermodynamic properties*. Intergovernmental Oceanographic Commission, Manuals and Guides No. 56, UNESCO (English), 196 pp.].

## 2. Installing the GSW Oceanographic Toolbox in MATLAB

### Step 1

Download the GSW Oceanographic Toolbox in MATLAB from [www.TEOS-10.org](http://www.TEOS-10.org).

### Step 2

Unzip the Toolbox to a directory you name "GSW".

**ENSURE THAT THE FOUR SUBFOLDERS (html, library, pdf, thermodynamics\_from\_t) HAVE ALSO BEEN EXTRACTED.**

### Step 3 (within MATLAB)

Add the "GSW" directory to your MATLAB path using "Add with subfolders ..."

That is, use the menus as follows "File" → "Set Path..." → "Add with subfolders ...". (Alternatively, the "addpath" command could be used).

**ENSURE THAT THE FOUR SUBFOLDERS (html, library, pdf, thermodynamics\_from\_t) HAVE ALSO BEEN ADDED TO THE PATH.**

### Step 4

Run `gsw_check_functions` to check that the Toolbox is correctly installed and that there are no conflicts. (This function runs three stored vertical profiles through all of the GSW functions, and checks that the outputs are within pre-defined limits of the correct values. These pre-defined limits are a factor of approximately a hundred larger than the errors expected from the numerical precision of different computers, at the standard double precision of MATLAB).

If the MATLAB Desktop is running,

### Step 5

Run `gsw_front_page` to gain access to the front page of the GSW Oceanographic Toolbox, which describes all aspects of the Toolbox.

Having installed the GSW Oceanographic Toolbox, the command `gsw_contents` will show the contents list of the software functions. The software descriptions and the help files for the GSW functions can be accessed by clicking on the function names on this list.

In addition, we have included a short demonstration function, `gsw_demo`, to introduce the user to the GSW Oceanographic Toolbox. `gsw_demo` uses two stored  $(S_p, t, p)$  profiles from the North Pacific and demonstrates, in a step-by-step manner, how to convert these into  $(S_A, \Theta, p)$  profiles. `gsw_demo` then demonstrates how to evaluate several water-column properties such as dynamic height, geostrophic streamfunction and geostrophic velocity, as well as forming potential density contours on the  $S_A - \Theta$  diagram.

A user may want to run `gsw_check_functions` periodically to confirm that the software remains uncorrupted.

### 3. Absolute Salinity $S_A$

Perhaps the most apparent change in using TEOS-10 compared with using the International Equation of State of seawater (EOS-80) is the adoption of Absolute Salinity  $S_A$  instead of Practical Salinity  $S_p$  (PSS-78) as the salinity argument for evaluating the thermodynamic properties of seawater. Importantly, Practical Salinity is retained as the salinity variable that is stored in national databases. This is done to maintain continuity in the archived salinity variable, and also because Practical Salinity is virtually the measured variable (whereas Absolute Salinity is a calculated variable).

The “raw” physical oceanographic data, as collected from ships and from autonomous platforms (e. g. Argo), and as stored in national oceanographic data bases, are

- Practical Salinity ( $S_p$ , unitless, PSS-78) and
- *in situ* temperature ( $t$ , °C, ITS-90) as functions of
- sea pressure ( $p$ , dbar), at a series of
- longitudes and latitudes.

Under TEOS-10 all the thermodynamic properties are functions of Absolute Salinity  $S_A$  (rather than of Practical Salinity), hence the first step in processing oceanographic data is to calculate Absolute Salinity, and this is accomplished by the GSW function **gsw\_SA\_from\_SP**. Hence the function **gsw\_SA\_from\_SP** is perhaps the most fundamental of the GSW functions as it is the gateway leading from oceanographic measurements to all the thermodynamic properties of seawater under TEOS-10. A call to this function can be avoided only if one is willing to ignore the influence of the spatial variations in the composition of seawater on seawater properties (such as density and specific volume). If this is indeed the intention, then the remaining GSW functions must be called with the salinity argument being Reference Salinity  $S_R$ , and most definitely, not with Practical Salinity  $S_p$ . Reference Salinity  $S_R$  can be obtained from the function **gsw\_SR\_from\_SP**.

The **gsw\_SA\_from\_SP**( $S_p, p, \text{long}, \text{lat}$ ) function first interpolates the global Absolute Salinity Anomaly Ratio ( $R^\delta$ ) data set using the internal GSW library function **gsw\_SAAR** to the ( $p, \text{long}, \text{lat}$ ) location. **gsw\_SA\_from\_SP** then uses this interpolated value of  $R^\delta$  to calculate Absolute Salinity  $S_A$  according to (see Eqn. (A.5.10) of appendix A.5 of the TEOS-10 Manual, IOC *et al.* (2010) and McDougall *et al.* (2012))

$$S_A = \frac{35.165\,04\text{ g kg}^{-1}}{35} S_p (1 + R^\delta). \quad \text{Non-Baltic} \quad (1)$$

In this expression  $(35.165\,04\text{ g kg}^{-1}/35) S_p$  is the Reference Salinity  $S_R$ , which is the best estimate of Absolute Salinity of a Standard Seawater sample.

Eqn. (1) is the value of Absolute Salinity returned by **gsw\_SA\_from\_SP** unless the function detects that the location is in the Baltic Sea (where incidentally the internal GSW library function **gsw\_SAAR** returns a value of  $R^\delta$  of zero). If the observation is from the Baltic Sea, the Absolute Salinity Anomaly  $\delta S_A$  is calculated according to  $S_A - S_R = 0.087\text{ g kg}^{-1} \times (1 - S_p/35)$  (from Eqn. (A.5.16) of IOC *et al.* (2010), following Feistel *et al.* (2010)), so that Absolute Salinity  $S_A$  is given by

$$S_A = \frac{(35.165\,04 - 0.087)\text{ g kg}^{-1}}{35} S_p + 0.087\text{ g kg}^{-1}. \quad \text{Baltic Sea} \quad (2)$$

In summary, the **gsw\_SA\_from\_SP** function returns either Eqn. (1) or Eqn. (2) depending on whether the longitude and latitude of the sample put the observation outside or inside the Baltic Sea. Since Practical Salinity should always be positive but there are sometimes a few negative values from a CTD, any negative input values of  $S_p$  to this function **gsw\_SA\_from\_SP** are set to zero.

If the latitude and longitude are such as to place the observation well away from the ocean, a flag ‘in\_ocean’ is set to zero as a warning, otherwise it is 1. This flag is only set when the observation is well and truly on dry land; often the warning flag is not set until

one is several hundred kilometers inland from the coast. When the function detects that the observation is not from the ocean,  $R^\delta$  is set equal to zero and `gsw_SA_from_SP` returns  $S_A = S_R = (35.165\ 04\ \text{g kg}^{-1}/35) S_p$  in accordance with Eqn. (1).

The largest influence of the variable seawater composition occurs in the northern North Pacific where  $S_A - S_R = \delta S_A$  is as large as  $0.027\ \text{g kg}^{-1}$  (see Figure 2 of IOC *et al.* (2010) which is reproduced below), this being the difference between Absolute Salinity and the estimate of Absolute Salinity which can be made on the basis of Practical Salinity alone. This increment of salinity equates to an increment of density of approximately  $0.020\ \text{kg m}^{-3}$ .

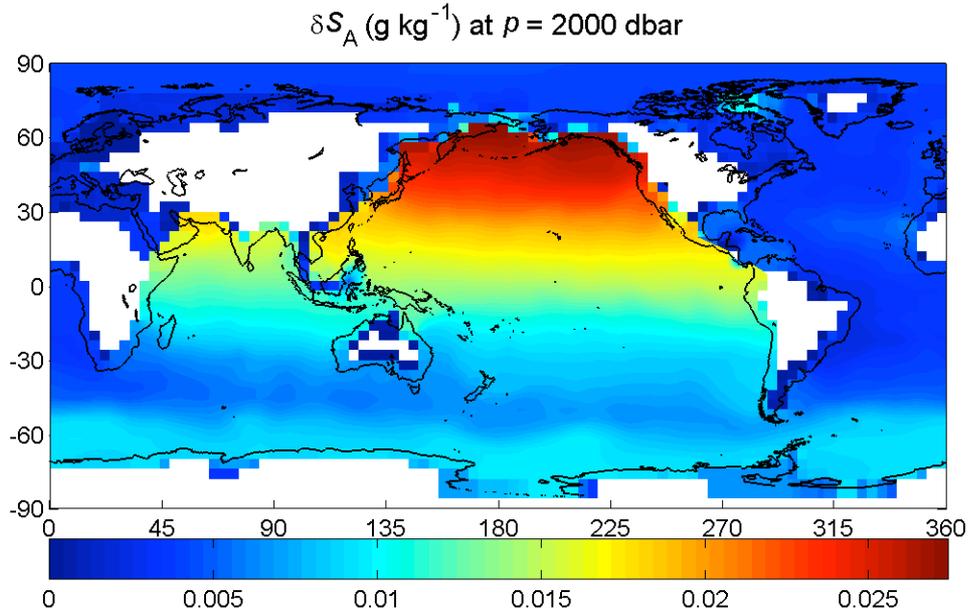


Figure 2 (a). Absolute Salinity Anomaly  $\delta S_A$  at  $p = 2000\ \text{dbar}$ .

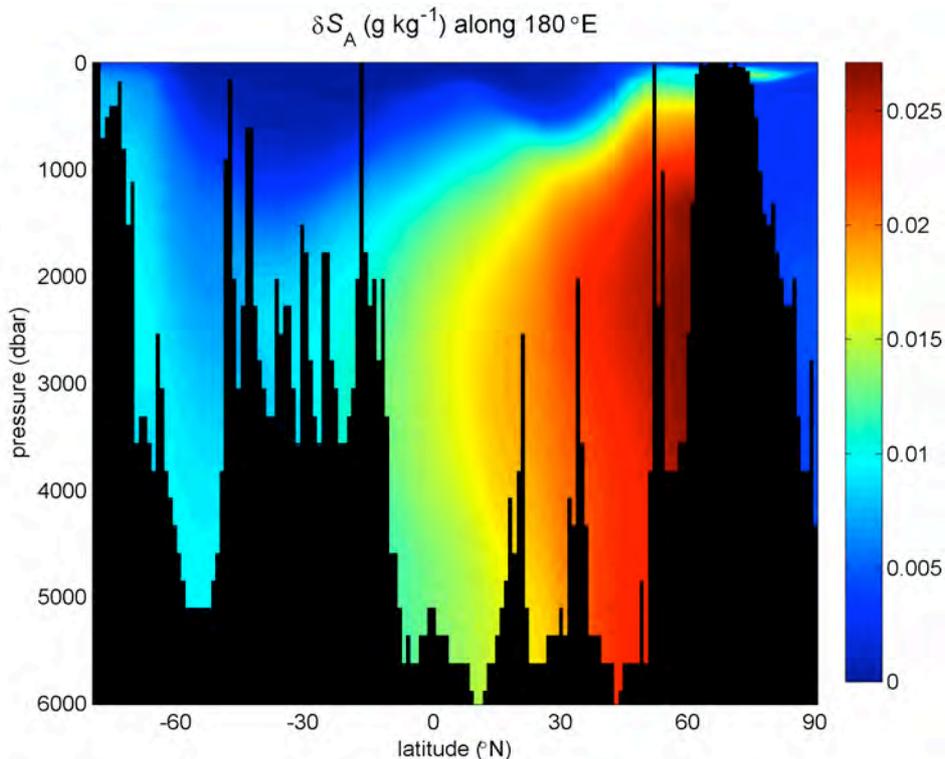
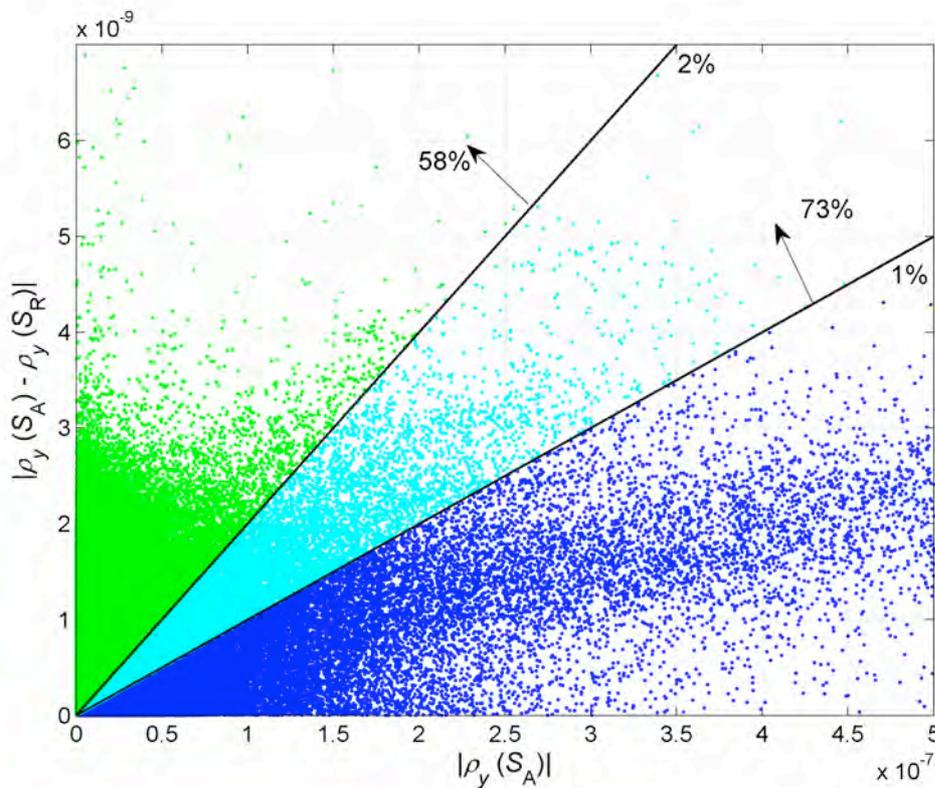


Figure 2 (b). A vertical section of Absolute Salinity Anomaly  $\delta S_A$  along  $180^\circ\text{E}$  in the Pacific Ocean.

In order to gauge the importance of the spatial variation of seawater composition, the northward gradient of density at constant pressure is reproduced below from Fig. A.5.1 of IOC *et al.* (2010) for the data in a world ocean hydrographic atlas deeper than 1000m. The vertical axis in this figure is the magnitude of the difference between the northward density gradient at constant pressure when the TEOS-10 algorithm for density is called with  $S_A$  (as it should be) compared with calling the same TEOS-10 density algorithm with  $S_R$  as the salinity argument. Figure A.5.1 shows that the “thermal wind” is misestimated by more than 2% for 58% of the data in the world ocean below a depth of 1000m if the effects of the variable seawater composition are ignored. When this same comparison is done for only the North Pacific, it is found that 60% of the data deeper than 1000m has “thermal wind” misestimated by more than 10% if  $S_R$  is used in place of  $S_A$ .

The first version of `gsw_SA_from_SP` was made available in January 2009 (then called `gsw_ASa1`). The second version (version 2.0) was released in October 2010 and superseded version 1. The third version (version 3.0) was released in May 2011 and supersedes version 2.0. This is unchanged in version 3.05 which was released in March 2015.



**Figure A.5.1.** The northward density gradient at constant pressure (the horizontal axis) for data in the global ocean atlas of Gouretski and Koltermann (2004) for  $p > 1000$  dbar. The vertical axis is the magnitude of the difference between evaluating the density gradient using  $S_A$  versus  $S_R$  as the salinity argument in the TEOS-10 expression for density.

As discussed in Pawlowicz (2010), Wright *et al.* (2011) and IOC *et al.* (2010), there are actually several contenders for the title of the “absolute salinity” of seawater, namely “Solution Salinity”, “Added-Mass Salinity”, and “Density Salinity”. The paper of Wright *et al.* (2011) presents a clear and readable account of this difficult subject, however the nuances surrounding these different definitions of absolute salinity need not concern most physical oceanographers. Under TEOS-10 the words Absolute Salinity and symbol  $S_A$  are reserved for “Density Salinity” such as can be deduced using laboratory measurements with a vibrating beam densimeter.

## 4. Performed Salinity $S_*$

Absolute Salinity  $S_A$ , Reference Salinity  $S_R$  and Practical Salinity  $S_p$  are all conservative salinity variables under the processes of (i) adiabatic pressure changes, and (ii) turbulent mixing, but none of these three salinity variables are conservative in the presence of (iii) biogeochemical processes. Performed Salinity  $S_*$  is designed to be a conservative salinity variable which is unaffected by biogeochemical activity in the ocean; it is defined as Absolute Salinity less the contributions of biogeochemical processes to Absolute Salinity.

The `gsw_Sstar_from_SP(SP,p,long,lat)` function first interpolates the global Absolute Salinity Anomaly Ratio ( $R^\delta$ ) data set using the internal GSW library function `gsw_SAAR` to the (p,long,lat) location. `gsw_Sstar_from_SP` then uses this interpolated value of  $R^\delta$  to calculate Performed Salinity  $S_*$  according to (see Eqn. (A.5.11) of appendix A.5 of the TEOS-10 Manual, IOC *et al.* (2010))

$$S_* = \frac{35.165\,04\text{ g kg}^{-1}}{35} S_p (1 - r_1 R^\delta), \quad \text{Non-Baltic} \quad (3)$$

where  $r_1$  is taken to be the constant 0.35 based on the work of Pawlowicz *et al.* (2011). Note that  $(35.165\,04\text{ g kg}^{-1}/35) S_p$  is Reference Salinity  $S_R$  which is the best estimate of Absolute Salinity for a Standard Seawater sample. The figure below (from Figure A.4.1 of the TEOS-10 Manual, IOC *et al.*, 2010) illustrates the relationships between Performed Salinity  $S_*$ , Reference Salinity  $S_R$  and Absolute Salinity  $S_A$ .



**Figure A.4.1.** Number line of salinity, illustrating the differences between Performed Salinity  $S_*$ , Reference Salinity  $S_R$ , and Absolute Salinity  $S_A$  for seawater whose composition differs from that of Standard Seawater.

Equation (3) is the value of Performed Salinity  $S_*$  returned by `gsw_Sstar_from_SP` unless the function detects that the location is in the Baltic Sea (where incidentally the internal GSW library function `gsw_SAAR` returns a value of  $R^\delta$  of zero). In the Baltic Sea the deviations of Absolute Salinity from Reference Salinity are not due to non-conservative biogeochemical processes but rather are due to the anomalous composition entering the Baltic from rivers. Since these anomalous constituents are conservative, Performed Salinity  $S_*$  in the Baltic Sea is Absolute Salinity  $S_A$ . Hence, if the observation is from the Baltic Sea, Performed Salinity  $S_*$  is calculated using the relation  $S_A - S_R = 0.087\text{ g kg}^{-1} \times (1 - S_p/35)$  (from Eqn. (A.5.6) of IOC *et al.* (2010), following Feistel *et al.* (2010)), so that

$$S_* = S_A = \frac{(35.165\,04 - 0.087)\text{ g kg}^{-1}}{35} S_p + 0.087\text{ g kg}^{-1}. \quad \text{Baltic Sea} \quad (4)$$

In summary, the `gsw_Sstar_from_SP` function returns either Eqn. (3) or Eqn. (4) depending on whether the longitude and latitude of the sample put the observation outside or inside the Baltic Sea. Since Practical Salinity should always be positive but there are sometimes be a few negative values from a CTD, any negative input values of  $S_p$  to this function `gsw_Sstar_from_SP` are set to zero.

If the latitude and longitude are such as to place the observation well away from the ocean, a flag ‘in\_ocean’ is set to zero as a warning, otherwise it is 1. This flag is only set when the observation is well and truly on dry land; often the warning flag is not set until one is several hundred kilometers inland from the coast. When the function detects that the observation is not from the ocean,  $R^\delta$  is set equal to zero and **gsw\_Sstar\_from\_SP** returns  $S_* = S_R = (35.165\ 04\ \text{g kg}^{-1}/35) S_P$  in accordance with Eqn. (3).

The largest influence of the variable seawater composition occurs in the northern North Pacific where  $S_R - S_*$  is almost  $0.01\ \text{g kg}^{-1}$ , and the difference between Absolute Salinity and the conservative Preformed Salinity,  $S_A - S_*$ , is as large as  $0.036\ \text{g kg}^{-1}$ , equivalent to an increment of density of approximately  $0.028\ \text{kg m}^{-3}$ .

Continuing to concentrate on the mid-depth northern North Pacific, recall that the salinity difference  $S_A - S_R = \delta S_A$  of  $0.027\ \text{g kg}^{-1}$  represents the difference between Absolute Salinity and the estimate of it using only Practical Salinity, while the value of  $S_A - S_*$  of  $0.036\ \text{g kg}^{-1}$  is the total influence of biogeochemical processes on Absolute Salinity. An ocean model which treats its salinity variable as being conservative needs to account for this salinity difference,  $S_A - S_*$ , before density and the “thermal wind” can be accurately calculated. The reason why the salinity differences  $S_A - S_R$  and  $S_A - S_*$  are not equal is that biogeochemical processes have an effect on the conductivity of seawater and therefore on Practical Salinity and Reference Salinity.

What then is the appropriate use of Preformed Salinity  $S_*$ ? This salinity variable is the one which can be treated as being conservative. Hence, in contrast to the evolution equation of Absolute Salinity  $S_A$ , the evolution equation for Preformed Salinity  $S_*$  does not contain non-conservative source terms caused by biogeochemistry (see appendix A.20 of IOC *et al.* (2010)). This means that Preformed Salinity  $S_*$  is ideal for use as

- (i) the salinity variable that is advected and diffused in forward ocean models,
- (ii) the salinity variable that is advected and diffused in inverse ocean models, and
- (iii) the salinity variable that is averaged when forming a hydrographic atlas.

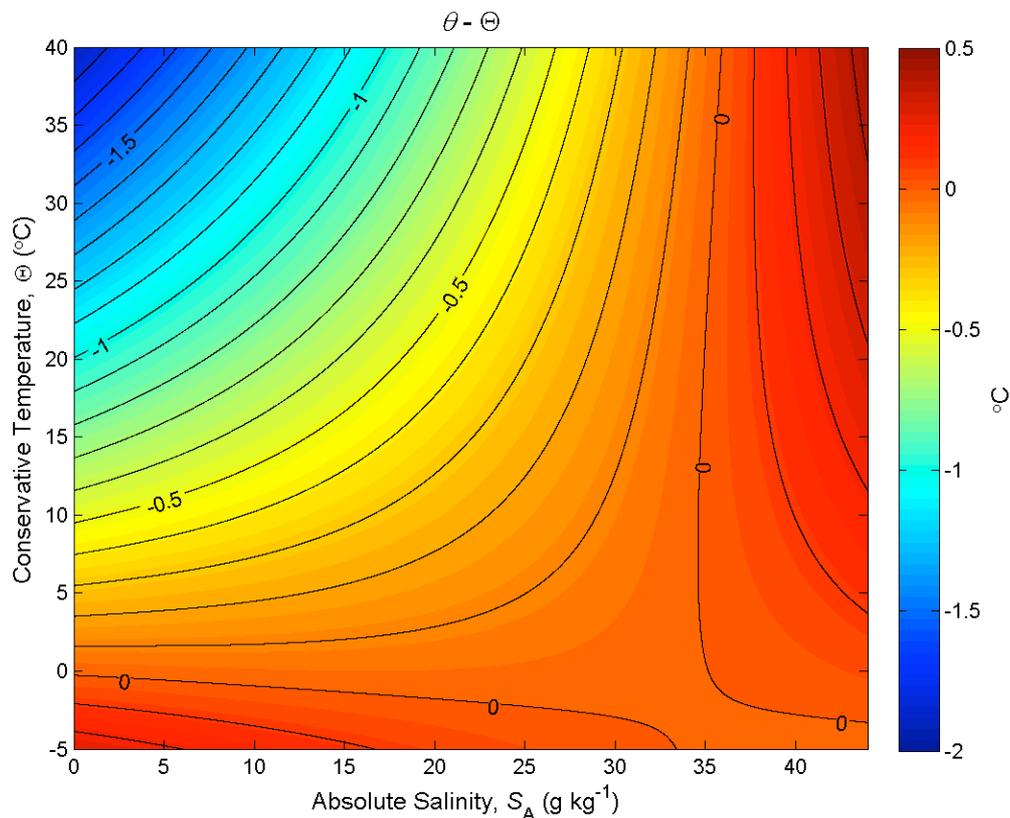
In these applications, the salinity difference  $S_A - S_*$  is added to the averaged atlas or model salinity variable to form Absolute Salinity  $S_A$  before other thermodynamic properties (such as density etc.) are calculated. Because of its conservative nature, there is an argument that suggests that Preformed Salinity  $S_*$  should be used in place of Absolute Salinity  $S_A$  as the salinity axis of the  $S_A - \Theta$  diagram, since water masses are notionally mixed on this diagram. However, to do so would take away the ability to draw isolines of potential density on this diagram, so the  $S_A - \Theta$  diagram (as opposed to the  $S_* - \Theta$  diagram) is recommended for water-mass analysis.

## 5. Conservative Temperature $\Theta$

Because the TEOS-10 properties of seawater are all derived from a Gibbs function, it is possible to find thermodynamic properties such as enthalpy, internal energy and entropy. Hence potential enthalpy and Conservative Temperature (which is simply proportional to potential enthalpy) are readily available.

Conservative Temperature is in some respects quite similar to potential temperature in that the same artificial thought experiment is involved with their definitions. In both cases one takes a seawater sample at an arbitrary pressure in the ocean and one imagines decreasing the pressure on the seawater parcel in an adiabatic and isohaline manner until the sea pressure  $p = 0$  dbar is reached. The temperature of the fluid parcel at the end of this artificial thought experiment is defined to be the potential temperature  $\theta$ . Similarly, the enthalpy at the end of this artificial thought experiment is defined to be the potential enthalpy  $h^0$ , and Conservative Temperature  $\Theta$  is simply potential enthalpy divided by the fixed “heat capacity”  $c_p^0 \equiv 3991.867\,957\,119\,63 \text{ J kg}^{-1} \text{ K}^{-1}$ .

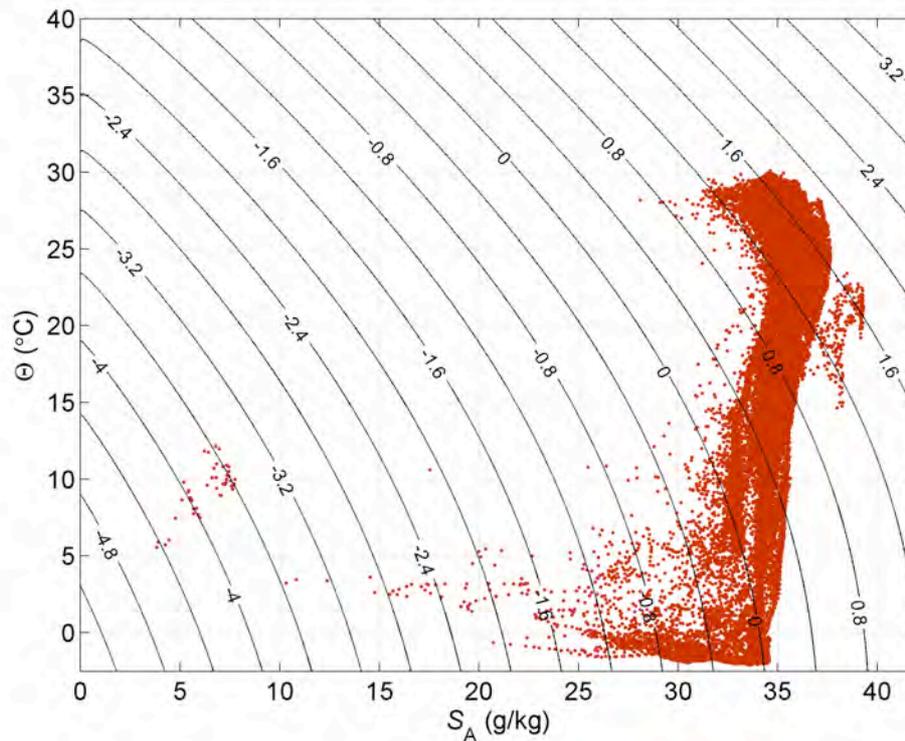
Conservative Temperature  $\Theta$  represents the “heat content” of seawater much more accurately than does potential temperature  $\theta$  (McDougall (2003), Graham and McDougall, 2013).  $\Theta$  can be evaluated from *in situ* temperature  $t$  from the function `gsw_CT_from_t`. The difference between potential temperature and Conservative Temperature can be as large as  $\theta - \Theta = -1.4^\circ\text{C}$  but is more typically no more than  $\pm 0.1^\circ\text{C}$  (see Figure A.17.1 of IOC *et al.* (2010) which is reproduced below). To put a temperature difference of  $0.1^\circ\text{C}$  in context, this is the typical difference between *in situ* and potential temperatures for a pressure difference of 1000 dbar, and it is approximately 40 times as large as the typical differences between  $t_{90}$  and  $t_{68}$  in the ocean.



**Figure A.17.1.** Contours (in  $^\circ\text{C}$ ) of the difference between potential temperature and Conservative Temperature  $\theta - \Theta$ . This plot illustrates the non-conservative production of potential temperature  $\theta$  in the ocean.

The air-sea heat flux is exactly proportional to the flux of Conservative Temperature, and because  $\Theta$  is almost a perfectly conservative variable, the meridional “heat” flux is very accurately given by the meridional flux of  $\Theta$  (as opposed to the meridional flux of potential temperature). Also, the parameterized lateral diffusion of “heat” along neutral tangent planes can be more than 1% different when such lateral diffusive heat fluxes are estimated using gradients of potential temperature rather than gradients of Conservative Temperature (see Figure A.14.1 of IOC *et al.* (2010) which is reproduced below).

For these reasons Conservative Temperature  $\Theta$  is the appropriate temperature variable to be used in ocean analyses. Just as Absolute Salinity  $S_A$  is now to be used in oceanographic publications instead of Practical Salinity, so too Conservative Temperature  $\Theta$  takes the place of potential temperature  $\theta$  under TEOS-10.



**Figure A.14.1.** Contours of  $(|\nabla_n \theta|/|\nabla_n \Theta| - 1) \times 100\%$  at  $p = 0$ , showing the percentage difference between the epineutral gradients of  $\theta$  and  $\Theta$ . The red dots are from the global ocean atlas of Gouretski and Koltermann (2004) at  $p = 0$ .

## 6. Which types of salinity and temperature should be archived?

Since 1978 we have gone to sea and collected and then archived Practical Salinity  $S_p$  (PSS-78), *in situ* temperature  $t$  (now ITS-90) and pressure  $p$  at known values of longitude, latitude and time. Under TEOS-10, nothing about this data collection and storage changes. Our instruments still need to measure properly calibrated data of  $(S_p, t, p)$  at known longitude, latitude and time. These are also exactly the same data that should continue to be archived in national oceanographic archives.

In particular, it cannot be over-emphasized that **NONE** of Reference Salinity  $S_R$ , Absolute Salinity  $S_A$  or Preformed Salinity  $S_*$  should **EVER** be submitted to or stored in national oceanographic databases. This resonates with present practice regarding temperature; we archive the measured quantity, *in situ* temperature  $t$ , not the calculated quantity, potential temperature  $\theta$ . Similarly, just as potential temperature is not stored in national databases, so too Conservative Temperature should **NEVER** be submitted to or stored in such national databases. In short, such databases should store measured (not calculated) quantities, and for this purpose, Practical Salinity is regarded as a measured quantity.

## 7. The 75-term expression $\hat{v}(S_A, \Theta, p)$ for specific volume

The computationally efficient 75-term polynomial for specific volume,  $\hat{v}(S_A, \Theta, p)$ , is described in Roquet *et al.* (2015), and is the function `gsw_specvol(SA,CT,p)` in the GSW Oceanographic Toolbox. Seawater specific volume data was fitted in a “funnel” of data points in  $(S_A, \Theta, p)$  space which is described in more detail in McDougall *et al.* (2003). The “funnel” extends to a pressure of 8000 dbar. At the sea surface the “funnel” covers the full range of temperature and salinity while for pressures greater than 6500 dbar, the maximum Conservative Temperature of the fitted data is 10°C and the minimum Absolute Salinity is 30 g kg<sup>-1</sup>. That is, the 75-term fit has been performed over a region of parameter space which includes water that is approximately 10°C warmer and 5 g kg<sup>-1</sup> fresher in the deep ocean than the seawater which exists in the present ocean.

The rms error of this 75-term approximation to the TEOS-10 density over the oceanographic “funnel” is 0.0002 kg m<sup>-3</sup>; this can be compared with the rms uncertainty of 0.004 kg m<sup>-3</sup> of the underlying laboratory density data to which the TEOS-10 Gibbs function was fitted. Similarly, the appropriate thermal expansion coefficient,

$$\alpha^\Theta = \frac{1}{v} \left. \frac{\partial v}{\partial \Theta} \right|_{S_A, p},$$

of the 75-term equation of state is different from the same thermal expansion coefficient evaluated directly from TEOS-10 with an rms error in the “funnel” of  $0.03 \times 10^{-6} \text{ K}^{-1}$ , compared with the rms error of the thermal expansion coefficient of the laboratory data to which the Feistel (2008) Gibbs function was fitted of  $0.73 \times 10^{-6} \text{ K}^{-1}$ . In terms of the evaluation of density gradients, the haline contraction coefficient evaluated from the 75-term equation is many times more accurate than the thermal expansion coefficient.

In dynamical oceanography it is the thermal expansion and haline contraction coefficients  $\alpha^\Theta$  and  $\beta^\Theta$  which are the most important aspects of the equation of state since the “thermal wind” is proportional to  $\alpha^\Theta \nabla_p \Theta - \beta^\Theta \nabla_p S_A$  and the vertical static stability is given in terms of the buoyancy frequency  $N$  by  $g^{-1} N^2 = \alpha^\Theta \Theta_z - \beta^\Theta (S_A)_z$ . Hence for dynamical oceanography the 75-term polynomial expression for specific volume retains essentially the full accuracy of TEOS-10. The use of the 75-term polynomial expression for specific volume has several advantages over using the exact formulation, namely

- it is a function of Conservative Temperature, so eliminating the need to be continually converting between Conservative and *in-situ* temperatures in order to evaluate density,
- it is computationally faster (by a factor of 4) to use the 75-term expression `gsw_specvol(SA,CT,p)` rather than using `gsw_specvol_CT_exact(SA,CT,p)` which is based on the sum of the Gibbs functions of pure water (IAPWS-09) and of sea salt (IAPWS-08),
- ocean models will use this 75-term equation of state, and it is advantageous for the fields of observational and theoretical oceanography to use the same equation of state as ocean models.

The functions of the GSW Oceanographic Toolbox are listed on the next four pages, after which section 8 begins on page 18.

# Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS - 10

## Practical Salinity (SP), PSS-78

gsw\_SP\_from\_C  
 gsw\_C\_from\_SP  
 gsw\_SP\_from\_R  
 gsw\_R\_from\_SP  
 gsw\_SP\_salinometer  
 gsw\_SP\_from\_SK

Practical Salinity from conductivity, C (incl. for SP < 2)  
 conductivity, C, from Practical Salinity (incl. for SP < 2)  
 Practical Salinity from conductivity ratio, R (incl. for SP < 2)  
 conductivity ratio, R, from Practical Salinity (incl. for SP < 2)  
 Practical Salinity from a laboratory salinometer (incl. for SP < 2)  
 Practical Salinity from Knudsen Salinity

## Absolute Salinity (SA), Preformed Salinity and Conservative Temperature (CT)

gsw\_SA\_from\_SP  
 gsw\_Sstar\_from\_SP  
 gsw\_CT\_from\_t

Absolute Salinity from Practical Salinity  
 Preformed Salinity from Practical Salinity  
 Conservative Temperature from in-situ temperature

## Absolute Salinity – Conservative Temperature plotting function

gsw\_SA\_CT\_plot

function to plot Absolute Salinity – Conservative Temperature profiles on the SA-CT diagram, including the freezing line and selected potential density contours

## other conversions between temperatures, salinities, entropy, pressure and height

gsw\_deltaSA\_from\_SP  
 gsw\_SA\_Sstar\_from\_SP  
 gsw\_SR\_from\_SP  
 gsw\_SP\_from\_SR  
 gsw\_SP\_from\_SA  
 gsw\_Sstar\_from\_SA  
 gsw\_SA\_from\_Sstar  
 gsw\_SP\_from\_Sstar  
 gsw\_pt\_from\_CT  
 gsw\_t\_from\_CT  
 gsw\_CT\_from\_pt  
 gsw\_pot\_enthalpy\_from\_pt  
 gsw\_pt\_from\_t  
 gsw\_pt0\_from\_t  
 gsw\_t\_from\_pt0  
 gsw\_t90\_from\_t48  
 gsw\_t90\_from\_t68  
 gsw\_z\_from\_p  
 gsw\_p\_from\_z  
 gsw\_z\_from\_depth  
 gsw\_depth\_from\_z  
 gsw\_Abs\_Pressure\_from\_p  
 gsw\_p\_from\_Abs\_Pressure  
 gsw\_entropy\_from\_CT  
 gsw\_CT\_from\_entropy  
 gsw\_entropy\_from\_pt  
 gsw\_pt\_from\_entropy  
 gsw\_entropy\_from\_t  
 gsw\_t\_from\_entropy  
 gsw\_adiabatic\_lapse\_rate\_from\_CT  
 gsw\_adiabatic\_lapse\_rate\_from\_t  
 gsw\_molality\_from\_SA  
 gsw\_ionic\_strength\_from\_SA

Absolute Salinity Anomaly from Practical Salinity  
 Absolute Salinity & Preformed Salinity from Practical Salinity  
 Reference Salinity from Practical Salinity  
 Practical Salinity from Reference Salinity  
 Practical Salinity from Absolute Salinity  
 Preformed Salinity from Absolute Salinity  
 Absolute Salinity from Preformed Salinity  
 Practical Salinity from Preformed Salinity  
 in-situ temperature from Conservative Temperature  
 Conservative Temperature from Conservative Temperature  
 potential temperature from potential temperature  
 potential enthalpy from potential temperature  
 potential temperature  
 potential temperature with reference pressure of 0 dbar  
 in-situ temperature from potential temperature with p\_ref of 0 dbar  
 ITS-90 temperature from IPTS-48 temperature  
 ITS-90 temperature from IPTS-68 temperature  
 height from pressure  
 pressure from height  
 height from depth  
 depth from height  
 Absolute Pressure, P, from sea pressure, p  
 sea pressure, p, from Absolute Pressure, P  
 entropy from Conservative Temperature  
 Conservative Temperature from entropy  
 entropy from potential temperature  
 potential temperature from entropy  
 entropy from in-situ temperature  
 in-situ temperature from entropy  
 adiabatic lapse rate from Conservative Temperature  
 adiabatic lapse rate from in-situ temperature  
 molality of seawater  
 ionic strength of seawater

## specific volume, density and enthalpy

gsw\_specvol  
 gsw\_alpha  
 gsw\_beta  
 gsw\_alpha\_on\_beta  
 gsw\_specvol\_alpha\_beta  
 gsw\_specvol\_first\_derivatives  
 gsw\_specvol\_second\_derivatives  
 gsw\_specvol\_first\_derivatives\_wrt\_enthalpy  
 gsw\_specvol\_second\_derivatives\_wrt\_enthalpy  
 gsw\_specvol\_anom  
 gsw\_specvol\_anom\_standard  
 gsw\_rho  
 gsw\_rho\_alpha\_beta  
 gsw\_rho\_first\_derivatives  
 gsw\_rho\_second\_derivatives  
 gsw\_rho\_first\_derivatives\_wrt\_enthalpy  
 gsw\_rho\_second\_derivatives\_wrt\_enthalpy  
 gsw\_sigma0  
 gsw\_sigma1  
 gsw\_sigma2  
 gsw\_sigma3  
 gsw\_sigma4  
 gsw\_cabbeling  
 gsw\_thermobaric  
 gsw\_enthalpy  
 gsw\_enthalpy\_diff  
 gsw\_dynamic\_enthalpy  
 gsw\_enthalpy\_first\_derivatives  
 gsw\_enthalpy\_second\_derivatives  
 gsw\_sound\_speed  
 gsw\_kappa  
 gsw\_internal\_energy  
 gsw\_internal\_energy\_first\_derivatives  
 gsw\_internal\_energy\_second\_derivatives  
 gsw\_CT\_from\_enthalpy  
 gsw\_SA\_from\_rho  
 gsw\_CT\_from\_rho  
 gsw\_CT\_maxdensity

specific volume  
 thermal expansion coefficient with respect to CT  
 saline contraction coefficient at constant CT  
 alpha divided by beta  
 specific volume, thermal expansion and saline contraction coefficients  
 first derivatives of specific volume  
 second derivatives of specific volume  
 first derivatives of specific volume with respect to enthalpy  
 second derivatives of specific volume with respect to enthalpy  
 specific volume anomaly  
 specific volume anomaly relative to SSO & 0°C  
 in-situ density and potential density  
 in-situ density, thermal expansion and saline contraction coefficients  
 first derivatives of density  
 second derivatives of density  
 first derivatives of density with respect to enthalpy  
 second derivatives of density with respect to enthalpy  
 sigma0 with reference pressure of 0 dbar  
 sigma1 with reference pressure of 1000 dbar  
 sigma2 with reference pressure of 2000 dbar  
 sigma3 with reference pressure of 3000 dbar  
 sigma4 with reference pressure of 4000 dbar  
 cabbeling coefficient  
 thermobaric coefficient  
 enthalpy  
 difference of enthalpy between two pressures  
 dynamic enthalpy  
 first derivatives of enthalpy  
 second derivatives of enthalpy  
 sound speed  
 isentropic compressibility  
 internal energy  
 first derivatives of internal energy  
 second derivatives of internal energy  
 Conservative Temperature from enthalpy  
 Absolute Salinity from density  
 Conservative Temperature from density  
 Conservative Temperature of maximum density of seawater

# Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS - 10

## vertical stability

gsw\_Nsquared  
gsw\_Turner\_Rsubrho  
gsw\_IPV\_vs\_fNsqared\_ratio

buoyancy (Brunt-Väisälä) frequency squared ( $N^2$ )  
Turner angle & Rsubrho  
ratio of the of isopycnal potential density to  $N^2$

## geostrophic streamfunctions, acoustic travel time and geostrophic velocity

gsw\_geo\_strf\_dyn\_height  
gsw\_geo\_strf\_dyn\_height\_pc  
gsw\_geo\_strf\_isopycnal  
gsw\_geo\_strf\_isopycnal\_pc

dynamic height anomaly  
dynamic height anomaly for piecewise constant profiles  
approximate isopycnal geostrophic streamfunction  
approximate isopycnal geostrophic streamfunction for piecewise constant profiles

gsw\_geo\_strf\_Cunningham  
gsw\_geo\_strf\_Montgomery  
gsw\_geo\_strf\_steric\_height  
gsw\_travel\_time  
gsw\_geostrophic\_velocity

Cunningham geostrophic streamfunction  
Montgomery geostrophic streamfunction  
dynamic height anomaly divided by  $9.7963 \text{ m s}^{-2}$   
acoustic travel time  
geostrophic velocity

## neutral versus isopycnal slopes and ratios

gsw\_isopycnal\_slope\_ratio  
gsw\_isopycnal\_vs\_ntp\_CT\_ratio  
gsw\_ntp\_pt\_vs\_CT\_ratio

ratio of the slopes of isopycnals on the SA-CT diagram for  $p$  &  $p_{ref}$   
ratio of the gradient of CT in a potential density surface to that in the neutral tangent plane  
ratio of gradients of  $pt$  &  $CT$  in a neutral tangent plane

## derivatives of entropy, CT and pt

gsw\_CT\_first\_derivatives  
gsw\_CT\_second\_derivatives  
gsw\_entropy\_first\_derivatives  
gsw\_entropy\_second\_derivatives  
gsw\_pt\_first\_derivatives  
gsw\_pt\_second\_derivatives

first derivatives of Conservative Temperature  
second derivatives of Conservative Temperature  
first derivatives of entropy  
second derivatives of entropy  
first derivatives of potential temperature  
second derivatives of potential temperature

## seawater and ice properties at freezing temperatures

gsw\_CT\_freezing  
gsw\_CT\_freezing\_poly  
gsw\_t\_freezing  
gsw\_t\_freezing\_poly  
gsw\_pot\_enthalpy\_ice\_freezing  
gsw\_pot\_enthalpy\_ice\_freezing\_poly  
gsw\_SA\_freezing\_from\_CT  
gsw\_SA\_freezing\_from\_CT\_poly  
gsw\_SA\_freezing\_from\_t  
gsw\_SA\_freezing\_from\_t\_poly  
gsw\_pressure\_freezing\_CT  
gsw\_CT\_freezing\_first\_derivatives  
gsw\_CT\_freezing\_first\_derivatives\_poly  
gsw\_t\_freezing\_first\_derivatives  
gsw\_t\_freezing\_first\_derivatives\_poly  
gsw\_pot\_enthalpy\_ice\_freezing\_first\_derivatives  
gsw\_pot\_enthalpy\_ice\_freezing\_first\_derivatives\_poly  
gsw\_latentheat\_melting

Conservative Temperature freezing temp of seawater  
Conservative Temperature freezing temp of seawater (poly)  
in-situ freezing temperature of seawater  
in-situ freezing temperature of seawater (poly)  
potential enthalpy of ice at which seawater freezes  
potential enthalpy of ice at which seawater freezes (poly)  
SA of seawater at the freezing temp (for given CT)  
SA of seawater at the freezing temp (for given CT) (poly)  
SA of seawater at the freezing temp (for given t)  
SA of seawater at the freezing temp (for given t) (poly)  
pressure of seawater at the freezing temp (for given CT)  
first derivatives of CT freezing temp of seawater  
first derivatives of CT freezing temp of seawater (poly)  
first derivatives of in-situ freezing temp of seawater  
first derivatives of in-situ freezing temp of seawater (poly)  
first derivatives of potential enthalpy of ice at freezing  
first derivatives of potential enthalpy of ice at freezing (poly)  
latent heat of melting of ice into seawater

## thermodynamic interaction between ice and seawater

gsw\_melting\_ice\_SA\_CT\_ratio  
gsw\_melting\_ice\_SA\_CT\_ratio\_poly  
gsw\_melting\_ice\_equilibrium\_SA\_CT\_ratio  
gsw\_melting\_ice\_equilibrium\_SA\_CT\_ratio\_poly  
gsw\_ice\_fraction\_to\_freeze\_seawater  
gsw\_melting\_ice\_into\_seawater  
gsw\_frazil\_ratios\_adiabatic  
gsw\_frazil\_ratios\_adiabatic\_poly  
gsw\_frazil\_properties  
gsw\_frazil\_properties\_potential  
gsw\_frazil\_properties\_potential\_poly

SA to CT ratio when ice melts into seawater  
SA to CT ratio when ice melts into seawater (poly)  
SA to CT ratio when ice melts, near equilibrium  
SA to CT ratio when ice melts, near equilibrium (poly)  
ice mass fraction to freeze seawater  
SA and CT when ice melts in seawater  
ratios of SA, CT and P changes during frazil ice formation  
ratios of SA, CT and P changes during frazil ice formation (poly)  
SA, CT & ice mass fraction from bulk SA & bulk enthalpy  
SA, CT & ice fraction from bulk SA & bulk potential enthalpy  
SA, CT & ice fraction from bulk SA & bulk potential enthalpy (poly)

## thermodynamic interaction between sea ice and seawater

gsw\_melting\_seaice\_SA\_CT\_ratio  
gsw\_melting\_seaice\_SA\_CT\_ratio\_poly  
gsw\_melting\_seaice\_equilibrium\_SA\_CT\_ratio  
gsw\_melting\_seaice\_equilibrium\_SA\_CT\_ratio\_poly  
gsw\_seaice\_fraction\_to\_freeze\_seawater  
gsw\_melting\_seaice\_into\_seawater

SA to CT ratio when sea ice melts into seawater  
SA to CT ratio when sea ice melts into seawater (poly)  
SA to CT ratio when sea ice melts, near equilibrium  
SA to CT ratio when sea ice melts, near equilibrium (poly)  
sea ice mass fraction to freeze seawater  
SA and CT when sea ice melts into seawater

## thermodynamic properties of ice Ih

gsw\_specvol\_ice  
gsw\_alpha\_wrt\_t\_ice  
gsw\_rho\_ice  
gsw\_pressure\_coefficient\_ice  
gsw\_sound\_speed\_ice  
gsw\_kappa\_ice  
gsw\_kappa\_const\_t\_ice  
gsw\_internal\_energy\_ice  
gsw\_enthalpy\_ice  
gsw\_entropy\_ice  
gsw\_cp\_ice  
gsw\_chem\_potential\_water\_ice  
gsw\_Helmholtz\_energy\_ice  
gsw\_adiabatic\_lapse\_rate\_ice  
gsw\_pt0\_from\_t\_ice  
gsw\_pt\_from\_t\_ice  
gsw\_t\_from\_pt0\_ice  
gsw\_t\_from\_rho\_ice  
gsw\_pot\_enthalpy\_from\_pt\_ice  
gsw\_pt\_from\_pot\_enthalpy\_ice  
gsw\_pot\_enthalpy\_from\_pt\_ice\_poly  
gsw\_pt\_from\_pot\_enthalpy\_ice\_poly  
gsw\_pot\_enthalpy\_from\_specvol\_ice  
gsw\_specvol\_from\_pot\_enthalpy\_ice  
gsw\_pot\_enthalpy\_from\_specvol\_ice\_poly  
gsw\_specvol\_from\_pot\_enthalpy\_ice\_poly

specific volume of ice  
thermal expansion coefficient of ice with respect to in-situ temp  
in-situ density of ice  
pressure coefficient of ice  
sound speed of ice (compression waves)  
isentropic compressibility of ice  
isothermal compressibility of ice  
internal energy of ice  
enthalpy of ice  
entropy of ice  
isobaric heat capacity of ice  
chemical potential of water in ice  
Helmholtz energy of ice  
adiabatic lapse rate of ice  
potential temperature of ice  
potential temperature of ice with reference pressure of 0 dbar  
in-situ temp from potential temp of ice with  $p_{ref}$  of 0 dbar  
in-situ temp from density of ice  
potential enthalpy from potential temperature of ice  
potential temperature from potential enthalpy of ice  
potential enthalpy from potential temperature of ice (poly)  
potential temperature from potential enthalpy of ice (poly)  
potential enthalpy from specific volume of ice  
specific volume from potential enthalpy of ice  
potential enthalpy from specific volume of ice (poly)  
specific volume from potential enthalpy of ice (poly)

# Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS - 10

## isobaric evaporation enthalpy

gsw\_latentheat\_evap\_CT latent heat of evaporation of water from seawater (isobaric evaporation enthalpy) with CT as input temperature  
 gsw\_latentheat\_evap\_t latent heat of evaporation of water from seawater (isobaric evaporation enthalpy) with in-situ temperature, t, as input

## spiciness

gsw\_spiciness0 spiciness with reference pressure of 0 dbar  
 gsw\_spiciness1 spiciness with reference pressure of 1000 dbar  
 gsw\_spiciness2 spiciness with reference pressure of 2000 dbar

## planet Earth properties

gsw\_f Coriolis parameter  
 gsw\_grav gravitational acceleration  
 gsw\_distance spherical earth distance between points in the ocean

## TEOS-10 constants

gsw\_T0 Celsius zero point; 273.15 K  
 gsw\_P0 one standard atmosphere; 101 325 Pa  
 gsw\_SSO Standard Ocean Reference Salinity; 35.165 04 g/kg  
 gsw\_uPS unit conversion factor for salinities; (35.165 04/35) g/kg  
 gsw\_cp0 the "specific heat" for use with CT; 3991.867 957 119 63 (J/kg)/K  
 gsw\_C3515 conductivity of SSW at SP=35, t\_68=15, p=0; 42.9140 mS/cm  
 gsw\_SonCl ratio of SP to Chlorinity; 1.80655 (g/kg)<sup>-1</sup>  
 gsw\_valence\_factor valence factor of sea salt; 1.2452898  
 gsw\_atomic\_weight mole-weighted atomic weight of sea salt; 31.4038218... g/mol

## dissolved gasses

gsw\_Arsol argon solubility from SA and CT  
 gsw\_Arsol\_SP\_pt argon solubility from SP and pt  
 gsw\_Hesol helium solubility from SA and CT  
 gsw\_Hesol\_SP\_pt helium solubility from SP and pt  
 gsw\_Krsol krypton solubility from SA and CT  
 gsw\_Krsol\_SP\_pt krypton solubility from SP and pt  
 gsw\_N2Osol nitrous oxide solubility from SA and CT  
 gsw\_N2Osol\_SP\_pt nitrous oxide solubility from SP and pt  
 gsw\_N2sol nitrogen solubility from SA and CT  
 gsw\_N2sol\_SP\_pt nitrogen solubility from SP and pt  
 gsw\_Nesol neon solubility from SA and CT  
 gsw\_Nesol\_SP\_pt neon solubility from SP and pt  
 gsw\_O2sol oxygen solubility from SA and CT  
 gsw\_O2sol\_SP\_pt oxygen solubility from SP and pt

## specific volume, density and enthalpy in terms of CT, based on the exact Gibbs function

gsw\_specvol\_CT\_exact specific volume  
 gsw\_alpha\_CT\_exact thermal expansion coefficient with respect to CT  
 gsw\_beta\_CT\_exact saline contraction coefficient at constant CT  
 gsw\_alpha\_on\_beta\_CT\_exact alpha divided by beta  
 gsw\_specvol\_alpha\_beta\_CT\_exact specific volume, thermal expansion and saline contraction coefficients  
 gsw\_specvol\_first\_derivatives\_CT\_exact first derivatives of specific volume  
 gsw\_specvol\_second\_derivatives\_CT\_exact second derivatives of specific volume  
 gsw\_specvol\_first\_derivatives\_wrt\_enthalpy\_CT\_exact first derivatives of specific volume with respect to enthalpy  
 gsw\_specvol\_second\_derivatives\_wrt\_enthalpy\_CT\_exact second derivatives of specific volume with respect to enthalpy  
 gsw\_specvol\_anom\_CT\_exact specific volume anomaly  
 gsw\_specvol\_anom\_standard\_CT\_exact specific volume anomaly relative to SSO & 0°C  
 gsw\_rho\_CT\_exact in-situ density and potential density  
 gsw\_rho\_alpha\_beta\_CT\_exact in-situ density, thermal expansion and saline contraction coefficients  
 gsw\_rho\_first\_derivatives\_CT\_exact first derivatives of density  
 gsw\_rho\_second\_derivatives\_CT\_exact second derivatives of density  
 gsw\_rho\_first\_derivatives\_wrt\_enthalpy\_CT\_exact first derivatives of density with respect to enthalpy  
 gsw\_rho\_second\_derivatives\_wrt\_enthalpy\_CT\_exact second derivatives of density with respect to enthalpy  
 gsw\_sigma0\_CT\_exact sigma0 with reference pressure of 0 dbar  
 gsw\_sigma1\_CT\_exact sigma1 with reference pressure of 1000 dbar  
 gsw\_sigma2\_CT\_exact sigma2 with reference pressure of 2000 dbar  
 gsw\_sigma3\_CT\_exact sigma3 with reference pressure of 3000 dbar  
 gsw\_sigma4\_CT\_exact sigma4 with reference pressure of 4000 dbar  
 gsw\_cabbeling\_CT\_exact cabbeling coefficient  
 gsw\_thermobaric\_CT\_exact thermobaric coefficient  
 gsw\_enthalpy\_CT\_exact enthalpy  
 gsw\_enthalpy\_diff\_CT\_exact difference of enthalpy between two pressures  
 gsw\_dynamic\_enthalpy\_CT\_exact dynamic enthalpy  
 gsw\_enthalpy\_first\_derivatives\_CT\_exact first derivatives of enthalpy  
 gsw\_enthalpy\_second\_derivatives\_CT\_exact second derivatives of enthalpy  
 gsw\_sound\_speed\_CT\_exact sound speed  
 gsw\_kappa\_CT\_exact isentropic compressibility  
 gsw\_internal\_energy\_CT\_exact internal energy  
 gsw\_internal\_energy\_first\_derivatives\_CT\_exact first derivatives of internal energy  
 gsw\_internal\_energy\_second\_derivatives\_CT\_exact second derivatives of internal energy  
 gsw\_CT\_from\_enthalpy\_exact Conservative Temperature from enthalpy  
 gsw\_SA\_from\_rho\_CT\_exact Absolute Salinity from density  
 gsw\_CT\_from\_rho\_exact Conservative Temperature from density  
 gsw\_CT\_maxdensity\_exact Conservative Temperature of maximum density of seawater

## laboratory functions, for use with densimeter measurements

gsw\_SA\_from\_rho\_t\_exact Absolute Salinity from density  
 gsw\_deltaSA\_from\_rho\_t\_exact Absolute Salinity Anomaly from density  
 gsw\_rho\_t\_exact in-situ density

# Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS - 10

## basic thermodynamic properties in terms of in-situ $t$ , based on the exact Gibbs function

<code>gsw_specvol_t_exact</code>	specific volume
<code>gsw_alpha_wrt_CT_t_exact</code>	thermal expansion coefficient with respect to Conservative Temperature
<code>gsw_alpha_wrt_pt_t_exact</code>	thermal expansion coefficient with respect to potential temperature
<code>gsw_alpha_wrt_t_exact</code>	thermal expansion coefficient with respect to in-situ temperature
<code>gsw_beta_const_CT_t_exact</code>	saline contraction coefficient at constant Conservative Temperature
<code>gsw_beta_const_pt_t_exact</code>	saline contraction coefficient at constant potential temperature
<code>gsw_beta_const_t_exact</code>	saline contraction coefficient at constant in-situ temperature
<code>gsw_specvol_anom_standard_t_exact</code>	specific volume anomaly relative to SSO & 0°C
<code>gsw_rho_t_exact</code>	in-situ density
<code>gsw_pot_rho_t_exact</code>	potential density
<code>gsw_sigma0_pt0_exact</code>	$\sigma_{00}$ from $\rho_{t0}$ with reference pressure of 0 dbar
<code>gsw_enthalpy_t_exact</code>	enthalpy
<code>gsw_dynamic_enthalpy_t_exact</code>	dynamic enthalpy
<code>gsw_CT_first_derivatives_wrt_t_exact</code>	first derivatives of Conservative Temperature with respect to $t$
<code>gsw_enthalpy_first_derivatives_wrt_t_exact</code>	first derivatives of enthalpy with respect to $t$
<code>gsw_sound_speed_t_exact</code>	sound speed
<code>gsw_kappa_t_exact</code>	isentropic compressibility
<code>gsw_kappa_const_t_exact</code>	isothermal compressibility
<code>gsw_internal_energy_t_exact</code>	internal energy
<code>gsw_SA_from_rho_t_exact</code>	Absolute Salinity from density
<code>gsw_t_from_rho_exact</code>	in-situ temperature from density
<code>gsw_t_maxdensity_exact</code>	in-situ temperature of maximum density of seawater
<code>gsw_cp_t_exact</code>	isobaric heat capacity
<code>gsw_isochoric_heat_cap_t_exact</code>	isochoric heat capacity
<code>gsw_chem_potential_relative_t_exact</code>	relative chemical potential
<code>gsw_chem_potential_water_t_exact</code>	chemical potential of water in seawater
<code>gsw_chem_potential_salt_t_exact</code>	chemical potential of salt in seawater
<code>gsw_t_deriv_chem_potential_water_t_exact</code>	temperature derivative of chemical potential of water
<code>gsw_dilution_coefficient_t_exact</code>	dilution coefficient of seawater
<code>gsw_Helmholtz_energy_t_exact</code>	Helmholtz energy
<code>gsw_osmotic_coefficient_t_exact</code>	osmotic coefficient of seawater
<code>gsw_osmotic_pressure_t_exact</code>	osmotic pressure of seawater

## Library functions of the GSW toolbox (internal functions; not intended to be called by users)

The GSW functions call the following library functions:

<code>gsw_gibbs</code>	the TEOS-10 Gibbs function of seawater and its derivatives
<code>gsw_gibbs_ice</code>	the TEOS-10 Gibbs function of ice and its derivatives
<code>gsw_SAAR</code>	Absolute Salinity Anomaly Ratio (excluding the Baltic Sea)
<code>gsw_Fdelta</code>	ratio of Absolute to Preformed Salinity, minus 1
<code>gsw_deltaSA_atlas</code>	Absolute Salinity Anomaly atlas value (excluding the Baltic Sea)
<code>gsw_SA_from_SP_Baltic</code>	Calculates Absolute Salinity in the Baltic Sea
<code>gsw_SP_from_SA_Baltic</code>	Calculates Practical Salinity in the Baltic Sea
<code>gsw_infunnel</code>	"oceanographic funnel" check for the 75-term equation
<code>gsw_entropy_part</code>	entropy minus the terms that are a function of only SA
<code>gsw_entropy_part_zero</code>	entropy_part evaluated at 0 dbar
<code>gsw_interp_ref_cast</code>	linearly interpolates the reference cast
<code>gsw_linear_interp_SA_CT</code>	linearly interpolates (SA,CT,p) to the desired p
<code>gsw_rr68_interp_SA_CT</code>	Reiniger & Ross (1968) interpolation of (SA,CT,p) to the desired p
<code>gsw_gibbs_pt0_pt0</code>	$\text{gibbs}(0,2,0,SA,t,0)$
<code>gsw_gibbs_ice_pt0_pt0</code>	part of $\text{gibbs\_ice}(1,0,t,p)$
<code>gsw_gibbs_ice_pt0</code>	part of $\text{gibbs\_ice}(1,0,pt0,0)$
<code>gsw_specvol_SSO_0</code>	$\text{specvol}(35.16504,0,p)$
<code>gsw_enthalpy_SSO_0</code>	$\text{enthalpy}(35.16504,0,p)$
<code>gsw_Hill_ratio_at_SP2</code>	Hill ratio at a Practical Salinity of 2

## The GSW data set:

`gsw_data_v3_0`

This file contains:

- (1) the global data set of Absolute Salinity Anomaly Ratio,
- (2) the global data set of Absolute Salinity Anomaly Ref.,
- (3) a reference cast (for the isopycnal streamfunction),
- (4) two reference casts that are used by `gsw_demo`
- (5) three vertical profiles of (SP, t, p) at known long & lat, plus the outputs of all the GSW functions for these 3 profiles, and the required accuracy of all these outputs.

## documentation set

`gsw_front_page`  
`gsw_check_functions`  
`gsw_demo`  
`gsw_ver`  
`gsw_licence`

front page to the GSW Oceanographic Toolbox  
 checks that all the GSW functions work correctly  
 demonstrates many GSW functions and features  
 displays the GSW version number  
 creative commons licence for the GSW Oceanographic Toolbox

The GSW Toolbox is available from  
[www.TEOS-10.org](http://www.TEOS-10.org)



IOC

## 8. 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  $\theta$  in order to analyze and publish water-mass characteristics on the  $S_p - \theta$  diagram. On this  $S_p - \theta$  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  $\Theta$ , which takes the place of potential temperature  $\theta$  (see section 5 above). Operationally, the calculation of Conservative Temperature  $\Theta$  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  $\Theta$  has the advantage over  $\theta$  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  $c_p^0 \equiv 3991.867\ 957\ 119\ 63\ \text{J kg}^{-1} \text{K}^{-1}$  times the density times the corresponding flux of  $\Theta$ . 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  $S_p - \theta$  diagram. Rather, because of the spatial variations of seawater composition, a given value of potential density defines an area on the  $S_p - \theta$  diagram, not a curved line. Hence for the analysis and publication of ocean data under TEOS-10 we need to change from using the  $S_p - \theta$  diagram which was appropriate under EOS-80, to using the  $S_A - \Theta$  diagram. It is on this  $S_A - \Theta$  diagram that the isolines of potential density can be drawn under TEOS-10.

Specific volume 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_specvol_CT_exact(SA,CT,p)` or from the 75-term polynomial expression using `gsw_specvol(SA,CT,p)`. The errors involved with using the 75-term expression for specific volume (or 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 75-term expression for specific volume 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 75-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 75-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 75-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,  $\omega$ -surfaces and

Neutral Density ( $\gamma^n$ ) surfaces) is **gsw\_geo\_strf\_isopycnal**. Also, it is this 75-term expression for specific volume that will be the basis for updated algorithms for  $\omega$ -surfaces (Klocker *et al.* (2010)) and Neutral Density  $\gamma^n$  (Jackett and McDougall (1997)).

In summary, under EOS-80 we have to date used the observed variables  $(S_p, t, p)$  to first form potential temperature  $\theta$  and then we have analyzed water masses on the  $S_p - \theta$  diagram, and we have been able to draw curved contours of potential density on this same  $S_p - \theta$  diagram. Under TEOS-10, the observed variables  $(S_p, t, p)$ , together with longitude and latitude, are used to first form Absolute Salinity  $S_A$  using **gsw\_SA\_from\_SP**, and then Conservative Temperature  $\Theta$  is calculated using **gsw\_CT\_from\_t**. Oceanographic water masses are then analyzed on the  $S_A - \Theta$  diagram (using **gsw\_SA\_CT\_plot**), and potential density contours can be drawn on this  $S_A - \Theta$  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  $\Theta$  in the GSW Oceanographic Toolbox, and all of the oceanographic variables in common use (including geostrophic streamfunctions) have been written using the 75-term expression for specific volume 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**.

## 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  $\Theta$  has these properties whereas potential temperature  $\theta$  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  $\Theta$  as  $\hat{\rho}(S_A, \Theta, p)$ , the interior of an ocean model can be written totally in terms of this one temperature variable,  $\Theta$ . 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  $\Theta$  to SST needs to be 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

$$S_* = S_R (1 - r_1 R^\delta), \quad (5)$$

$$S_A = S_* (1 + F^\delta), \quad (6)$$

where

$$R^\delta \equiv \frac{\delta S_A^{\text{atlas}}}{S_R^{\text{atlas}}} \quad \text{and} \quad F^\delta = \frac{[1 + r_1] R^\delta}{(1 - r_1 R^\delta)}. \quad (7a, b)$$

The Absolute Salinity Anomaly Ratio,  $R^\delta \equiv \delta S_A^{\text{atlas}} / S_R^{\text{atlas}}$ , is the ratio of the values of Absolute Salinity Anomaly and Reference Salinity in the stored hydrographic atlas.

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)),

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

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  $\gamma_z^{-1}$  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  $R^\delta$ ; 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  $F^\delta$

$$\frac{dF^\delta}{dt} = \gamma_z \nabla_n \cdot \left( \gamma_z^{-1} K \nabla_n F^\delta \right) + \left( D \frac{\partial F^\delta}{\partial z} \right)_z + \tau^{-1} \left( F^{\delta \text{obs}} - F^\delta \right). \quad (9)$$

The model variable  $F^\delta$  (note that  $F^\delta = S_A/S_* - 1$ ) is initialized based on observations of  $R^\delta \equiv \delta S_A^{\text{atlas}} / S_R^{\text{atlas}}$  and the use of Eqn. (7b); this is best done by calling `gsw_Fdelta`. Equation (9) shows that  $F^\delta$  is advected and diffused like any other tracer, but in addition, there is a non-conservative source term  $\tau^{-1} (F^{\delta \text{obs}} - F^\delta)$  which serves to restore the model variable  $F^\delta$  towards the observed value (found from `gsw_Fdelta`) with a restoring time  $\tau$  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  $F^\delta$ , while  $\hat{S}_A$  is calculated from these two model variables at each time step according to

$$\hat{S}_A = \hat{S}_* (1 + F^\delta). \quad (10)$$

It is this salinity,  $\hat{S}_A$ , 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  $S_A = S_*$  and the value of Absolute Salinity Anomaly  $\delta S_A$  is immaterial during the running of the model. Of course the values of  $\delta S_A$  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).

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  $\Theta$ ,  $\hat{v}(S_A, \Theta, p)$ , such as the 75-term expression to be found in **gsw\_specvol**(SA,CT,p),
- (ii) have Conservative Temperature  $\Theta$  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  $\Theta$ ,
- (v) model output salinities and temperatures are best made as Absolute Salinity  $S_A$  and Conservative Temperature  $\Theta$ , consistent with the variables which will be published in oceanographic journals.

## 10. A guide to the GSW Oceanographic Toolbox

The key attributes of the three oceanographic variables  $S_A$ ,  $S_*$  and  $\Theta$  may be summarized as follows. Preformed Salinity  $S_*$  and Conservative Temperature  $\Theta$  are the ideal variables for representing the "salt content" and "heat content" of seawater in the standard conservation equations of physical oceanography. However, the thermodynamic properties of seawater (in particular, density) depend not on Preformed Salinity  $S_*$ , but rather on Absolute Salinity  $S_A$ . While Practical Salinity  $S_p$  is relatively easy to measure accurately, it should now be regarded as a stepping stone on the way to calculating the two more attractive salinity variables,  $S_A$  and  $S_*$ .

The GSW functions are listed on the central four pages of this document. The group of functions "Practical Salinity (SP), PSS-78" contains routines for Practical Salinity in terms of either conductivity  $C$  or conductivity ratio  $R$ , as well as their inverse functions. The input temperature to these functions is *in situ* temperature (ITS-90), and the inverse algorithms are iterated until the Practical Salinity is equal to the input value to within  $2 \times 10^{-14}$ , that is, to machine precision. These functions incorporate a modified form of the extension of Hill *et al.* (1986) to Practical Salinities between zero and 2. The modification ensures that the algorithm is exactly PSS-78 for  $S_p \geq 2$  and is continuous at  $S_p = 2$ . The function in this group, **gsw\_SP\_salinometer**, calculates Practical Salinity from the two outputs of a laboratory salinometer, namely  $R_t$  and the bath temperature.

The second group delivers the three new oceanographic variables, Absolute Salinity  $S_A$ , Preformed Salinity  $S_*$ , and Conservative Temperature  $\Theta$ . The first two functions have Practical Salinity  $S_p$ , pressure, longitude and latitude as input variables. Note that virtually all of the functions which follow this second group require Absolute Salinity  $S_A$  as an input. Hence it is clear that when analyzing oceanic data, the very first function call must be to **gsw\_SA\_from\_SP**. Hence this function is the most fundamental in the GSW toolbox. This function can be avoided only by ignoring the influence of the spatial variations of seawater composition, in which case the remaining GSW functions would be called with Reference Salinity  $S_R$  (given by calling **gsw\_SR\_from\_SP**) in place of  $S_A$ . The function **gsw\_CT\_from\_t** evaluates Conservative Temperature  $\Theta$ , as a function of Absolute Salinity  $S_A$ , *in situ* temperature  $t$  and pressure  $p$ .

The third group contains just the function **gsw\_SA\_CT\_plot** which plots the TEOS-10 version of the "T-S" diagram for a series of vertical profiles. The Conservative Temperature at the freezing point for  $p = 0$  dbar, and user-selected potential density contours are also displayed on this  $S_A - \Theta$  diagram using the 75-term expression for the density of seawater, **gsw\_rho**(SA,CT,p).

The fourth grouping of functions has the heading “other conversions between temperatures, salinities, entropy, pressure and height”. Some of these functions are the reverse of those in the previous groups (namely **gsw\_SP\_from\_SA**, **gsw\_SP\_from\_Sstar** and **gsw\_t\_from\_CT**) while others perform familiar functions such as **gsw\_pt\_from\_t**(SA,t,p,p\_ref) which evaluates the potential temperature of the “bottle” (SA,t,p) referenced to the pressure p\_ref.

The next group of functions (the right-hand side of the page), headed “specific volume, density and enthalpy”, are all derived from the computationally-efficient 75-term expression for specific volume,  $\hat{v}(S_A, \Theta, p)$  of Roquet *et al.* (2015). This group includes the function **gsw\_rho** to evaluate both density and potential density, and **gsw\_alpha** to evaluate the relevant thermal expansion coefficient. This 75-term expression for specific volume is essentially as accurate as the full TEOS-10 expression, and this 75-term expression has the advantage that its temperature argument is Conservative Temperature. The functions **gsw\_enthalpy** and **gsw\_enthalpy\_diff** are used when evaluating various geostrophic streamfunctions, since under isentropic and isohaline conditions, enthalpy is the pressure integral of specific volume. The functions **gsw\_SA\_from\_rho** and **gsw\_CT\_from\_rho** are essentially the inverse functions of the equation of state in that they return the Absolute Salinity (or Conservative Temperature respectively) for given values of density, pressure and either  $\Theta$  or  $S_A$  respectively.

The next group of three functions, headed “vertical stability”, delivers variables which are defined in terms of the vertical gradients of  $S_A$  and  $\Theta$  on an individual vertical profile, and so are inherently water column properties. These functions deliver the square of the buoyancy frequency (**gsw\_Nsquared**), the Turner angle, and the ratio of the vertical gradient of potential density to the vertical gradient of locally-referenced potential density.

The following group is for calculating four different geostrophic streamfunctions, and the acoustic travel time for sound up and down a vertical water column. All of these GSW geostrophic streamfunction functions have  $S_A$  and  $\Theta$  as their input salinity and temperature. It is important to realize that a particular geostrophic streamfunction is only accurate when used in the surface for which it is derived. For example, dynamic height anomaly is the geostrophic streamfunction in an isobaric surface while the Montgomery streamfunction is the geostrophic streamfunction in a specific volume anomaly surface. When one is working in some type of approximately neutral surface, the Cunningham geostrophic streamfunction is more accurate than the Montgomery streamfunction, while the “isopycnal” geostrophic streamfunction **gsw\_geo\_strf\_isopycnal** of McDougall and Klocker (2010) is the most accurate (see Figures 1, 2 and 3 of McDougall and Klocker (2010)). The functions in this group all use the 75-term polynomial for specific volume.

The next group contains just the one function, **gsw\_geostrophic\_velocity**, which calculates the geostrophic velocity in a given surface with respect to the velocity in a reference surface. This function should be called with dynamic height anomaly if the surface in which the geostrophic velocity is required is an isobaric surface. Similarly, **gsw\_geostrophic\_velocity** should be called with the “isopycnal” geostrophic streamfunction **gsw\_geo\_strf\_isopycnal** if the surface in which the geostrophic velocity is evaluated is an approximately neutral surface (such as a Neutral Density surface (Jackett and McDougall (1997)), an  $\omega$ -surface (Klocker *et al.* (2010)) or a potential density surface).

The next group of functions is concerned with various neutral attributes of the seawater equation of state and returns properties such as the ratio of the gradient of Conservative Temperature in a potential density surface to that in the neutral tangent plane.

The following group “derivatives of entropy, CT and pt” contains functions which use the full TEOS-10 Gibbs function and have a variety of input temperatures, appropriate to the variable being differentiated. The outputs of these functions are used, for example, in evaluating the amount of non-conservative production associated with each variable (entropy, CT and pt) when two seawater parcels are mixed.

The following four groups give properties of ice, of sea ice, and of the thermodynamic equilibrium between seawater and either ice or sea ice. These four groups are followed by a group of functions which gives the latent heats of melting and of evaporation.

The next group “spiciness” delivers the spiciness variable for three different reference pressures. Spiciness is a measure of the change of water-mass properties along a potential density surface.

The group, “planet Earth properties”, delivers straightforward properties of the rotating planet of the solar system on which we presently reside.

The group “TEOS-10 constants” simply returns various constants which are basic to TEOS-10. Note that the constant **gsw\_C3515** is not a fundamental constant of either PSS-78 or TEOS-10 but is required to convert a measured conductivity value  $C$  into conductivity ratio  $R$  (which *is* a fundamental property of PSS-78).

The group “dissolved gases” contains algorithms for the solubility of various gases. This is not work that resulted from SCOR/IAPSO Working Group 127, nor have these algorithms been approved by IOC. These algorithms are included in the GSW Oceanographic Toolbox as they seem to be oceanographic best practice.

The two groups on the right-hand side of this third page contain only functions evaluated using the full TEOS-10 Gibbs function (being the sum of the IAPWS-09 and IAPWS-08 Gibbs functions). The group of GSW functions, headed “specific volume, density and enthalpy in terms of CT, based on the exact Gibbs function” delivers exactly the same outputs as the corresponding group on page one based on the 75-term expression for specific volume,  $\hat{v}(S_A, \Theta, p)$ , having also the same inputs as those functions. The functions in this group can be used to confirm that the use of the 75-term computationally efficient equation of state does not noticeably degrade any output property.

The group of GSW functions headed “laboratory functions, for use with densimeter measurements”. These functions have *in situ* temperature  $t$  as their input temperature variable. All three functions in this group use the full TEOS-10 Gibbs function, namely the sum of the Gibbs functions of IAPWS-09 and IAPWS-08 (rather than the 75-term expression for specific volume).

The fourth page of the GSW algorithms list include the “basic thermodynamic properties in terms of in-situ  $t$ , based on the exact Gibbs function” in which can be found many of the basic thermodynamic properties of seawater. Each of these functions have *in situ* temperature as the input temperature variable. The next group contains the library functions used by GSW. These are internal functions which are not intended to be called by users. There is nothing stopping a skilled operator using these programs, but unless the user is confident, it is safer to access these library routines via one of the public functions; for example, there is little or no checking on the array sizes of the input variables in these internal library functions. The data set `gsw_data_v3_0` must not be tampered with.

The function **gsw\_check\_functions** confirms that the GSW Oceanographic Toolbox is correctly installed and that there are no conflicts. This function runs three stored vertical profiles through of all the other GSW functions, and checks that the outputs are within predefined limits of the correct answers. These pre-defined limits are a factor of approximately a hundred larger than the errors expected from numerical round-off (at the standard double precision of MATLAB). The user may want to run **gsw\_check\_functions** periodically to confirm that the software remains uncorrupted. **gsw\_demo** runs and displays results from several of the GSW functions, so introducing the user to some of the features of the Toolbox.

The GSW Oceanographic Toolbox is designed to be comprehensive and to be installed in its entirety, even though most users may use relatively few of the functions for routine oceanographic analyses. For example, the most basic use of the GSW Oceanographic Toolbox would begin with a data set of  $(S_p, t, p)$  at known longitudes and latitudes. The first steps are to call **gsw\_SA\_from\_SP** and then **gsw\_CT\_from\_t** to convert to a data set of

$(S_A, \Theta, p)$ . With the data set in this form, water masses may be analyzed accurately on the  $S_A - \Theta$  diagram, and *in situ* density and potential density are available by calling the computationally-efficient 75-term expression for density, `gsw_rho`, with the pressure input being the *in situ* sea pressure  $p$ , and the reference sea pressure  $p_{\text{ref}}$ , respectively. That is, *in situ* density is evaluated as `gsw_rho(SA,CT,p)` and potential density with respect to the reference pressure  $p_{\text{ref}}$  is given by `gsw_rho(SA,CT,p_ref)`.

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## 12. Recommended nomenclature, symbols and units in oceanography

This section 12 is from appendix L of the TEOS-10 Manual, IOC *et al.* (2010).

### L.1 Recommended nomenclature

The strict SI units of Absolute Salinity, temperature and pressure are  $\text{kg kg}^{-1}$ , Absolute Temperature in K and Absolute Pressure  $P$  in Pa. These are the units predominantly adopted in the SIA computer software for the input and output variables. If oceanographers were to adopt this practice of using strictly SI quantities it would simplify many thermodynamic expressions at the cost of using unfamiliar units.

The GSW Oceanographic Toolbox (appendix N) adopts as far as possible the currently used oceanographic units, so that the input variables for all the computer algorithms are Absolute Salinity in  $S_A$  in  $\text{g kg}^{-1}$ , temperature in  $^{\circ}\text{C}$  and pressure as sea pressure in dbar. The outputs of the functions are also generally consistent with this choice of units, but some variables are more naturally expressed in SI units.

It seems impractical to recommend that the field of oceanography fully adopt strict basic SI units. It is however very valuable to have the field adopt uniform symbols and units, and in the interests of achieving this uniformity we recommend the following symbols and units. These are the symbols and units we have adopted in the GSW Oceanographic Toolbox.

**Table L.1. Recommended Symbols and Units in Oceanography**

Quantity	Symbol	Units	Comments
Chlorinity	$Cl$	$\text{g kg}^{-1}$	<i>Chlorinity</i> is defined as the following mass fraction; it is 0.328 523 4 times the ratio of the mass of pure silver required to precipitate all dissolved chloride, bromide and iodide in seawater to the mass of seawater.
Standard Ocean Reference Salinity	$S_{\text{SO}}$	$\text{g kg}^{-1}$	35.165 04 $\text{g kg}^{-1}$ being exactly 35 $\mu_{\text{PS}}$ , corresponding to the standard ocean Practical Salinity of 35.
freezing temperatures	$t^f, \Theta^f$	$^{\circ}\text{C}$	<i>in situ</i> and conservative values, each as a function of $S_A$ and $p$ .
Absolute Pressure	$P$	Pa	When Absolute Pressure is used it should always be in Pa, not in Mpa nor in dbar.
sea pressure. Sea pressure is the pressure argument to all the GSW Toolbox functions.	$p$	dbar	Equal to $P - P^0$ and usually expressed in dbar not Pa.

gauge pressure. Gauge pressure (also called applied pressure) is sometimes reported from ship-born instruments.	$p^{\text{gauge}}$	dbar	Equal to the Absolute Pressure $P$ minus the local atmospheric pressure at the time of the instrument calibration, and expressed in dbar not Pa. Sea pressure $p$ is preferred over gauge pressure $p^{\text{gauge}}$ , as $p$ is the argument to the seawater Gibbs function.
reference pressure	$P_r$	dbar	The value of the sea pressure $p$ to which potential temperature and/or potential density are referenced.
one standard atmosphere	$P_0$	Pa	exactly 101 325 Pa (= 10.1325 dbar)
isopycnal slope ratio	$r$	1	$r = \frac{\alpha^\ominus(p)/\beta^\ominus(p)}{\alpha^\ominus(p_r)/\beta^\ominus(p_r)}$
Stability Ratio	$R_\rho$	1	$R_\rho = \alpha^\ominus\Theta_z/\beta^\ominus(S_A)_z \approx \alpha^\theta\theta_z/\beta^\theta(S_A)_z$ .
isopycnal temperature gradient ratio	$G^\ominus$	1	$G^\ominus = r[R_\rho - 1]/[R_\rho - r]$ ; $\nabla_\sigma\Theta = G^\ominus\nabla_n\Theta$
Practical Salinity	$S_p$	1	Defined in the range $2 < S_p < 42$ by PSS-78 based on measured conductivity ratios.
Reference Salinity	$S_R$	$\text{g kg}^{-1}$	Reference-Composition Salinity (or Reference Salinity for short) is the Absolute Salinity of seawater samples that have Reference Composition. At $S_p = 35$ , $S_R$ is exactly $u_{\text{PS}}S_p$ while in the range $2 < S_p < 42$ $S_R \approx u_{\text{PS}}S_p$ .
Absolute Salinity (This is the salinity argument of all the GSW Toolbox functions.)	$S_A = S_A^{\text{dens}}$	$\text{g kg}^{-1}$	$S_A = S_R + \delta S_A \approx u_{\text{PS}}S_p + \delta S_A$ Absolute Salinity is the sum of $S_R$ on the Millero <i>et al.</i> (2008a) Reference-Salinity Scale and the Absolute Salinity Anomaly. The full symbol for $S_A$ is $S_A^{\text{dens}}$ as it is the type of absolute salinity which delivers the best estimate of density when used as the salinity argument of the TEOS-10 Gibbs function. Another name for $S_A = S_A^{\text{dens}}$ is “Density Salinity”.
Absolute Salinity Anomaly	$\delta S_A$	$\text{g kg}^{-1}$	$\delta S_A = S_A - S_R$ , the difference between Absolute Salinity, $S_A = S_A^{\text{dens}}$ , and Reference-Composition Salinity. In terms of the full nomenclature of Pawlowicz <i>et al.</i> (2010), Wright <i>et al.</i> (2010b) and appendix A.4 herein, the Absolute Salinity Anomaly $\delta S_A$ is $\delta S_R^{\text{dens}}$ .
“Preformed Absolute Salinity”, often shortened to “Preformed Salinity”	$S_*$	$\text{g kg}^{-1}$	Preformed Absolute Salinity $S_*$ is a salinity variable that is designed to be as conservative as possible, by removing the estimated biogeochemical influences on the seawater composition from other forms of salinity (see Pawlowicz <i>et al.</i> (2010), Wright <i>et al.</i> (2010b)).
“Solution Absolute Salinity”, often shortened to “Solution Salinity”	$S_A^{\text{soln}}$	$\text{g kg}^{-1}$	The mass fraction of non-H <sub>2</sub> O constituents in seawater after it has been brought to chemical equilibrium at $t = 25^\circ\text{C}$ and $p = 0$ dbar (see Pawlowicz <i>et al.</i> (2010), Wright <i>et al.</i> (2010b)).
“Added-Mass Salinity”	$S_A^{\text{add}}$	$\text{g kg}^{-1}$	$S_A^{\text{add}} - S_R$ is the estimated mass fraction of non-H <sub>2</sub> O constituents needed as ingredients to be added to Standard Seawater which when mixed and brought to chemical equilibrium at $t = 25^\circ\text{C}$ and $p = 0$ dbar results in the observed seawater composition.

temperature	$t$	°C	
Absolute Temperature	$T$	K	$T / \text{K} \equiv T_0 / \text{K} + t / (^\circ\text{C}) = 273.15 + t / (^\circ\text{C})$
temperature derivatives	$T$	K	When a quantity is differentiated with respect to <i>in situ</i> temperature, the symbol $T$ is used in order to distinguish this variable from time.
Celsius zero point	$T_0$	K	$T_0 \equiv 273.15 \text{ K}$
potential temperature	$\theta$	°C	Defined implicitly by Eqn. (3.1.3)
Conservative Temperature	$\Theta$	°C	Defined in Eqn. (3.3.1) as exactly potential enthalpy divided by $c_p^0$ .
the “specific heat”, for use with Conservative Temperature	$c_p^0$	$\text{J kg}^{-1} \text{K}^{-1}$	$c_p^0 \equiv 3991.867\,957\,119\,63 \text{ J kg}^{-1} \text{K}^{-1}$ . This 15-digit number is defined to be the exact value of $c_p^0$ . $c_p^0$ is the ratio of potential enthalpy $h^0$ to $\Theta$ .
combined standard uncertainty	$u_c$	Varies	
enthalpy	$H$	J	
specific enthalpy	$h$	$\text{J kg}^{-1}$	$h = u + (p + P_0)v$ . Here $p$ and $P_0$ must be in Pa not dbar.
specific potential enthalpy	$h^0$	$\text{J kg}^{-1}$	specific enthalpy referenced to zero sea pressure, $h^0 = h(S_A, \theta[S_A, t, p, p_r = 0], p_r = 0)$
specific isobaric heat capacity	$c_p$	$\text{J kg}^{-1} \text{K}^{-1}$	$c_p = \partial h / \partial T _{S_A, p}$
internal energy	$U$	J	
specific internal energy	$u$	$\text{J kg}^{-1}$	
specific isochoric heat capacity	$c_v$	$\text{J kg}^{-1} \text{K}^{-1}$	$c_v = \partial u / \partial T _{S_A, v}$
Gibbs function (Gibbs energy)	$G$	J	
specific Gibbs function (Gibbs energy)	$g$	$\text{J kg}^{-1}$	
specific Helmholtz energy	$f$	$\text{J kg}^{-1}$	
unit conversion factor for salinities	$u_{\text{PS}}$	$\text{g kg}^{-1}$	$u_{\text{PS}} \equiv (35.16504/35) \text{ g kg}^{-1} \approx 1.004\,715\dots \text{ g kg}^{-1}$ The first part of this expression is exact. This conversion factor is an important and invariant constant of the 2008 Reference-Salinity Scale (Millero <i>et al.</i> (2008a)).
entropy	$\Sigma$	$\text{J K}^{-1}$	
specific entropy	$\eta$	$\text{J kg}^{-1} \text{K}^{-1}$	In many other publications the symbol $s$ is used for specific entropy.
density	$\rho$	$\text{kg m}^{-3}$	
density anomaly	$\sigma^t$	$\text{kg m}^{-3}$	$\rho(S_A, t, 0) - 1000 \text{ kg m}^{-3}$
potential density anomaly referenced to a sea pressure of 2000 dbar	$\sigma_2$	$\text{kg m}^{-3}$	$\rho(S_A, \theta[S_A, t, p, p_r], p_r) - 1000 \text{ kg m}^{-3}$ where $p_r = 2000 \text{ dbar}$
potential density anomaly referenced to a sea pressure of 4000 dbar	$\sigma_4$	$\text{kg m}^{-3}$	$\rho(S_A, \theta[S_A, t, p, p_r], p_r) - 1000 \text{ kg m}^{-3}$ where $p_r = 4000 \text{ dbar}$
thermal expansion coefficient with respect to <i>in situ</i> temperature	$\alpha^t$	$\text{K}^{-1}$	$v^{-1} \partial v / \partial T _{S_A, p} = -\rho^{-1} \partial \rho / \partial T _{S_A, p}$
thermal expansion coefficient with respect to potential temperature $\theta$	$\alpha^\theta$	$\text{K}^{-1}$	$v^{-1} \partial v / \partial \theta _{S_A, p} = -\rho^{-1} \partial \rho / \partial \theta _{S_A, p}$

thermal expansion coefficient with respect to Conservative Temperature $\Theta$	$\alpha^\ominus$	$\text{K}^{-1}$	$v^{-1}\partial v / \partial \Theta _{S_A, p} = -\rho^{-1}\partial \rho / \partial \Theta _{S_A, p}$
saline contraction coefficient at constant <i>in situ</i> temperature	$\beta^t$	$\text{kg g}^{-1}$	$-v^{-1}\partial v / \partial S_A _{T, p} = \rho^{-1}\partial \rho / \partial S_A _{T, p}$ Note that the units for $\beta^t$ are consistent with $S_A$ being in $\text{g kg}^{-1}$ .
saline contraction coefficient at constant potential temperature	$\beta^\theta$	$\text{kg g}^{-1}$	$-v^{-1}\partial v / \partial S_A _{\theta, p} = \rho^{-1}\partial \rho / \partial S_A _{\theta, p}$ Note that the units for $\beta^\theta$ are consistent with $S_A$ being in $\text{g kg}^{-1}$ .
saline contraction coefficient at constant Conservative Temperature	$\beta^\ominus$	$\text{kg g}^{-1}$	$-v^{-1}\partial v / \partial S_A _{\ominus, p} = +\rho^{-1}\partial \rho / \partial S_A _{\ominus, p}$ Note that the units for $\beta^\ominus$ are consistent with $S_A$ being in $\text{g kg}^{-1}$ .
isothermal compressibility	$\kappa^t$	$\text{Pa}^{-1}$	
isentropic and isohaline compressibility	$\kappa$	$\text{Pa}^{-1}$	
chemical potential of water in seawater	$\mu^w$	$\text{J g}^{-1}$	
chemical potential of sea salt in seawater	$\mu^s$	$\text{J g}^{-1}$	
relative chemical potential of (sea salt and water in) seawater	$\mu$	$\text{J g}^{-1}$	$(\partial g / \partial S_A)_{t, p} = \mu^s - \mu^w$
dissipation rate of kinetic energy per unit mass	$\varepsilon$	$\text{J kg}^{-1} \text{s}^{-1}$ $= \text{m}^2 \text{s}^{-3}$	
adiabatic lapse rate	$\Gamma$	$\text{K Pa}^{-1}$	$\Gamma = \frac{\partial t}{\partial P} _{S_A, \theta} = \frac{\partial t}{\partial P} _{S_A, \ominus} = \frac{\partial t}{\partial P} _{S_A, \eta} = \frac{\partial v}{\partial \eta} _{S_A, p} = \frac{(T_0 + \theta)}{c_p^0} \frac{\partial v}{\partial \Theta} _{S_A, p}$
sound speed	$c$	$\text{m s}^{-1}$	
specific volume	$v$	$\text{m}^3 \text{kg}^{-1}$	$v = \rho^{-1}$
specific volume anomaly	$\delta$	$\text{m}^3 \text{kg}^{-1}$	
thermobaric coefficient based on $\theta$	$T_b^\theta$	$\text{K}^{-1} \text{Pa}^{-1}$	$T_b^\theta = \beta^\theta \partial (\alpha^\theta / \beta^\theta) / \partial P _{S_A, \theta}$
thermobaric coefficient based on $\Theta$	$T_b^\ominus$	$\text{K}^{-1} \text{Pa}^{-1}$	$T_b^\ominus = \beta^\ominus \partial (\alpha^\ominus / \beta^\ominus) / \partial P _{S_A, \ominus}$
cabbeling coefficient based on $\theta$	$C_b^\theta$	$\text{K}^{-2}$	$C_b^\theta = \partial \alpha^\theta / \partial \theta _{S_A, p} + 2 \frac{\alpha^\theta}{\beta^\theta} \partial \alpha^\theta / \partial S_A _{\theta, p} - \left(\frac{\alpha^\theta}{\beta^\theta}\right)^2 \partial \beta^\theta / \partial S_A _{\theta, p}$
cabbeling coefficient based on $\Theta$	$C_b^\ominus$	$\text{K}^{-2}$	$C_b^\ominus = \partial \alpha^\ominus / \partial \Theta _{S_A, p} + 2 \frac{\alpha^\ominus}{\beta^\ominus} \partial \alpha^\ominus / \partial S_A _{\ominus, p} - \left(\frac{\alpha^\ominus}{\beta^\ominus}\right)^2 \partial \beta^\ominus / \partial S_A _{\ominus, p}$
buoyancy frequency	$N$	$\text{s}^{-1}$	$N^2 = g (\alpha^\ominus \Theta_z - \beta^\ominus S_{A_z}) = g (\alpha^\theta \theta_z - \beta^\theta S_{A_z})$
neutral helicity	$H^n$	$\text{m}^{-3}$	defined by Eqns. (3.13.1) and (3.13.2)
Neutral Density	$\gamma^n$	$\text{kg m}^{-3}$	a density variable whose iso-surfaces are designed to be approximately neutral, i. e. $\alpha^\ominus \nabla_\gamma \Theta \approx \beta^\ominus \nabla_\gamma S_A$ .
Neutral-Surface-Potential-Vorticity	$NSPV$	$\text{s}^{-3}$	$NSPV = -g \rho^{-1} f \gamma_z^n$ where $f$ is the Coriolis parameter.
dynamic height anomaly	$\Psi$	$\text{m}^2 \text{s}^{-2}$	$\text{Pa m}^3 \text{kg}^{-1} = \text{m}^2 \text{s}^{-2}$
Montgomery geostrophic streamfunction	$\Psi^M$	$\text{m}^2 \text{s}^{-2}$	$\text{Pa m}^3 \text{kg}^{-1} = \text{m}^2 \text{s}^{-2}$

PISH (Pressure-Integrated Steric Height)	$\Psi'$	$\text{kg s}^{-2}$	streamfunction for $f$ times the depth-integrated relative mass flux, see Eqns. (3.31.1) – (3.31.5).
Coriolis parameter	$f$	$\text{s}^{-1}$	$1.458\,42 \times 10^{-4} \sin \phi \text{ s}^{-1}$ , where $\phi$ is latitude
molar mass of Reference Seawater	$M_S$	$\text{g mol}^{-1}$	$M_S$ is the mole-weighted average atomic weight of the constituents of Reference Seawater, $M_S = 31.403\,821\,8\dots \text{g mol}^{-1}$ , from Millero <i>et al.</i> (2008a).
molality of seasalt in Reference Seawater	$m_{\text{SW}}$	$\text{mol kg}^{-1}$	$m_{\text{SW}} = \sum_i m_i = \frac{1}{M_S} \frac{S_A}{(1-S_A)}$ . $m_i$ is the molality of constituent $i$ in Reference Seawater.
valence factor of Reference Seawater	$Z^2$	1	$Z^2 = \sum_i X_i Z_i^2 \equiv 1.245\,289\,8$ where $Z_i$ is the charge of seawater constituent $i$ which is present at the mole fraction $X_i$ in Reference Seawater (from Millero <i>et al.</i> (2008a)).
ionic strength of Reference Seawater	$I$	$\text{mol kg}^{-1}$	$I = \frac{1}{2} m_{\text{SW}} Z^2 = \frac{1}{2} \sum_i m_i Z_i^2$ $= 0.622\,644\,9 m_{\text{SW}}$ $\approx \frac{0.622\,644\,9}{0.031\,403\,821\,8} \text{mol kg}^{-1} \frac{S_A}{(1-S_A)}$ $m_i$ is the molality of constituent $i$ in Reference Seawater.
osmotic coefficient	$\phi$	1	$\phi(S_A, T, p) = \frac{g(0, t, p) - \mu^{\text{W}}(S_A, t, p)}{m_{\text{SW}} R (T_0 + t)}$ <p>where the molar gas constant, <math>R = 8.314\,472 \text{ J mol}^{-1} \text{ K}^{-1}</math>. See also Eqns. (2.14.1) and (3.40.9) for an equivalent definition of <math>\phi</math>.</p>

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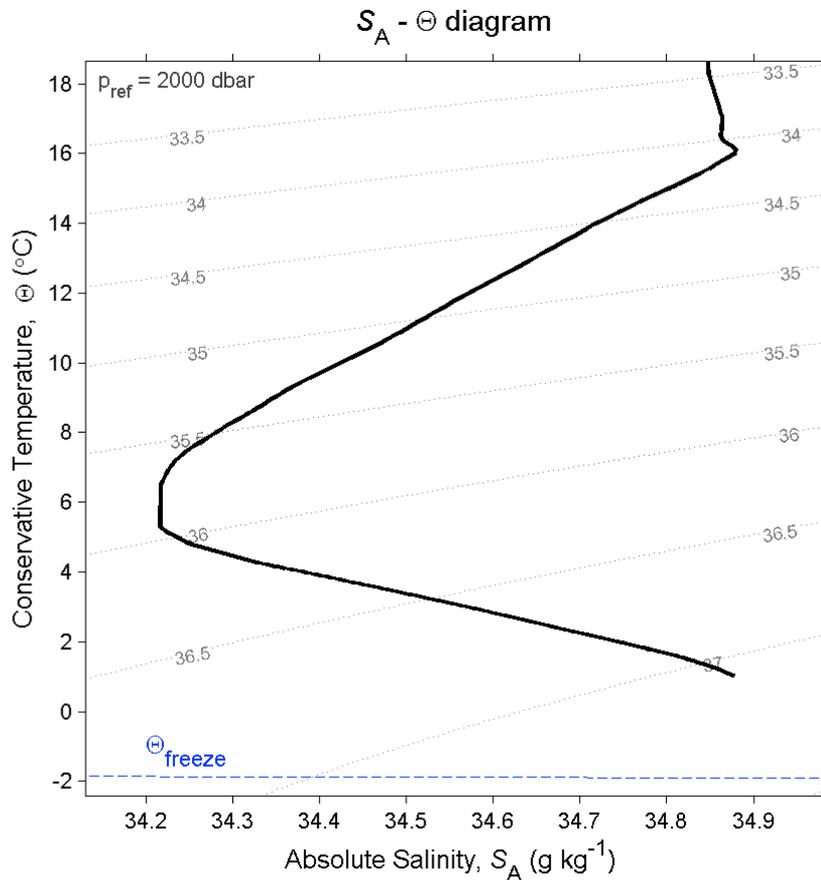
## TEOS-10 and GSW in a nutshell

In order to analyse oceanographic data under TEOS-10, the observed values of Practical Salinity  $S_p$  and *in situ* temperature  $t$  need to be converted into Absolute Salinity  $S_A$  and Conservative Temperature  $\Theta$ , as follows,

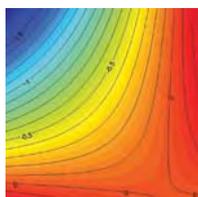
**Step 1.** calculate Absolute Salinity,  $S_A = \text{gsw\_SA\_from\_SP}(S_p, p, \text{long}, \text{lat})$ ,

**Step 2.** calculate Conservative Temperature,  $\Theta = \text{gsw\_CT\_from\_t}(S_A, t, p)$ .

Having converted  $(S_p, t, p)$  to  $(S_A, \Theta, p)$ , the GSW functions listed on page 14 of this document are then used for analysing the data. The use of these GSW functions ensures consistency between theoretical oceanography, observational oceanography and ocean modelling.



Under TEOS-10, the  $S_A - \Theta$  diagram is the new "T-S" diagram. The above  $S_A - \Theta$  diagram was plotted using `gsw_SA_CT_plot`. The  $\sigma_2$  potential density anomaly contours were evaluated inside this function using `gsw_rho(SA,CT,2000)`. This same function can be used to evaluate *in situ* density via `gsw_rho(SA,CT,p)`.



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