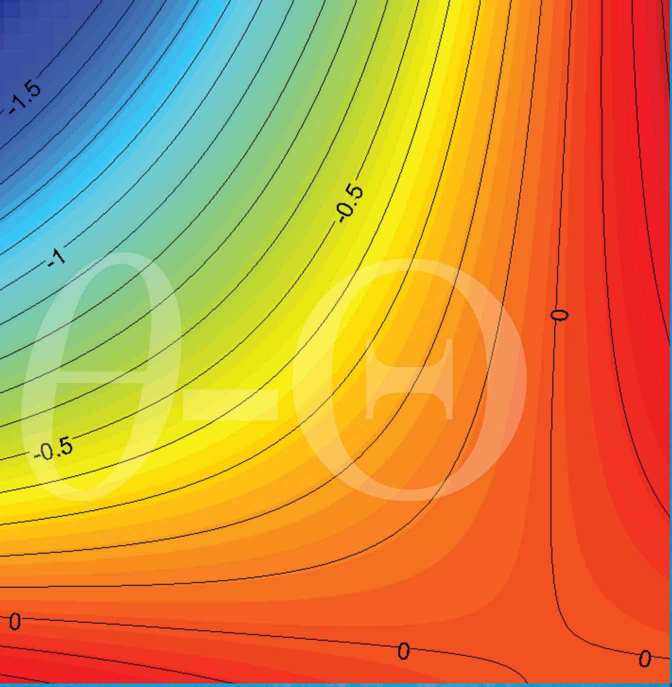


Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox

VERSION 3.06.12

July 2020

International Council for Science
SCOR
Scientific Committee on Oceanic Research
IAPSO
UNESCO
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.

Trevor J. McDougall, (chair), University of New South Wales, Sydney, Australia
Rainer Feistel, Leibniz-Institut fuer Ostseeforschung, Warnemuende, Germany
Daniel G. Wright+, formerly of Bedford Institute of Oceanography, Dartmouth, Canada
Rich Pawlowicz, University of British Columbia, Vancouver, Canada
Frank J. Millero, University of Miami, Florida, USA
David R. Jackett++, formerly of CSIRO, Hobart, Australia
Brian A. King, National Oceanography Centre, Southampton, UK
Giles M. Marion, Desert Research Institute, Reno, USA
Steffen Seitz, Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
Petra Spitzer, Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
C-T. Arthur Chen, National Sun Yat-Sen University, Taiwan, R.O.C.

+ deceased, 8th July 2010
++ deceased, 31st March 2012

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.

For bibliographic purposes, this document should be cited as follows:

McDougall T. J. and P. M. Barker, 2011: Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox, 28pp., SCOR/IAPSO WG127, ISBN 978-0-646-55621-5.

This document is available from www.TEOS-10.org

May 2011

Author: McDougall, Trevor J.
Title: Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox / Trevor J. McDougall and Paul M. Barker.
ISBN: 9780646556215 (pbk.)
Subjects: Gibbs Seawater (GSW) Oceanographic Toolbox (Computer program)
Seawater--Thermodynamics--Computer programs
Other Authors/Contributors: Barker, Paul M.
Dewey Number: 551.46

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

version 3.06.12

Trevor J. McDougall[1] and Paul M. Barker[1]

May 2011, updated July 2020 with the release of
version 3.06.12 of the GSW Oceanographic Toolbox

Table of Contents

page

---

[1] School of Mathematics and Statistics, University of New South Wales, Sydney, Australia
email: Trevor.McDougall@unsw.edu.au

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 Θ. 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 θ 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 Θ, which takes the place of potential temperature θ. Conservative Temperature Θ has the advantage over θ 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 Θ 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. $\mathrm{g\ kg^{-1}}$).
- 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 Θ accurately represents the "heat content" per unit mass of seawater, and is to be used in place of potential temperature θ 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 $\hat{v}(S_\mathrm{A},\Theta,p)$) 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 Θ, 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.

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.

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

Download and install an optimisation solver if you wish to use the 2 stabilisation functions, **gsw_stabilise_SA_CT** and **gsw_stabilise_SA_const_t**.
We recommend Tomlab CPLEX or IBM ILOG CPLEX Optimization Studio.
Tomlab is available from http://tomopt.com/tomlab/
IBM ILOG CPLEX Optimization Studio is free for academics and students through their academic initiative program and is available from https://ibm.onthehub.com

Step 5

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 6

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 $(S_{\mathrm{A}}, \Theta, p)$ 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 $S_{\mathrm{A}} - \Theta$ 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**(SP,p,long,lat) function first interpolates the global Absolute Salinity Anomaly Ratio (R^{δ}) data set using the internal GSW library function **gsw_SAAR** to the (p,long,lat) location. **gsw_SA_from_SP** then uses this interpolated value of R^{δ} 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))

$$S_A \;=\; \frac{35.165\,04\ \mathrm{g\,kg^{-1}}}{35}\; S_P\left(1 + R^{\delta}\right). \qquad \textit{Non-Baltic} \qquad (1)$$

In this expression $\left(35.165\,04\ \mathrm{g\,kg^{-1}}/35\right) S_P$ 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^{δ} of zero). If the observation is from the Baltic Sea, the Absolute Salinity Anomaly δS_A is calculated according to $S_A - S_R = \ 0.087\,\mathrm{g\,kg^{-1}} \times \left(1 - S_P/35\right)$ (from Eqn. (A.5.16) of IOC *et al.* (2010), following Feistel *et al.* (2010)), so that Absolute Salinity S_A is given by

$$S_A \;=\; \frac{\left(35.165\,04\ -\ 0.087\right)\mathrm{g\,kg^{-1}}}{35}\, S_P \;+\; 0.087\ \mathrm{g\,kg^{-1}}. \qquad \textit{Baltic Sea} \qquad (2)$$

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^{δ} is set equal to zero and **gsw_SA_from_SP** returns $S_{\mathrm{A}} = S_{\mathrm{R}} = \left(35.165\,04\ \mathrm{g\,kg^{-1}}/35\right) S_{\mathrm{P}}$ in accordance with Eqn. (1).

The largest influence of the variable seawater composition occurs in the northern North Pacific where $S_{\mathrm{A}} - S_{\mathrm{R}} = \delta S_{\mathrm{A}}$ is as large as $0.027\ \mathrm{g\ kg^{-1}}$ (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 $0.020\ \mathrm{kg\ m^{-3}}$.

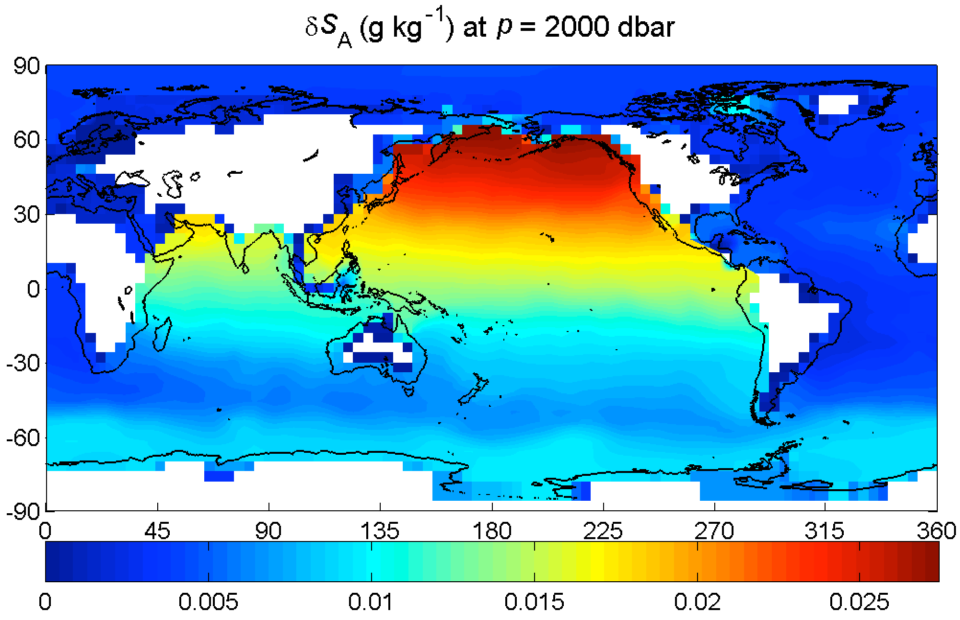


Figure 2 (a). Absolute Salinity Anomaly δS_{A} at $p = 2000$ dbar.

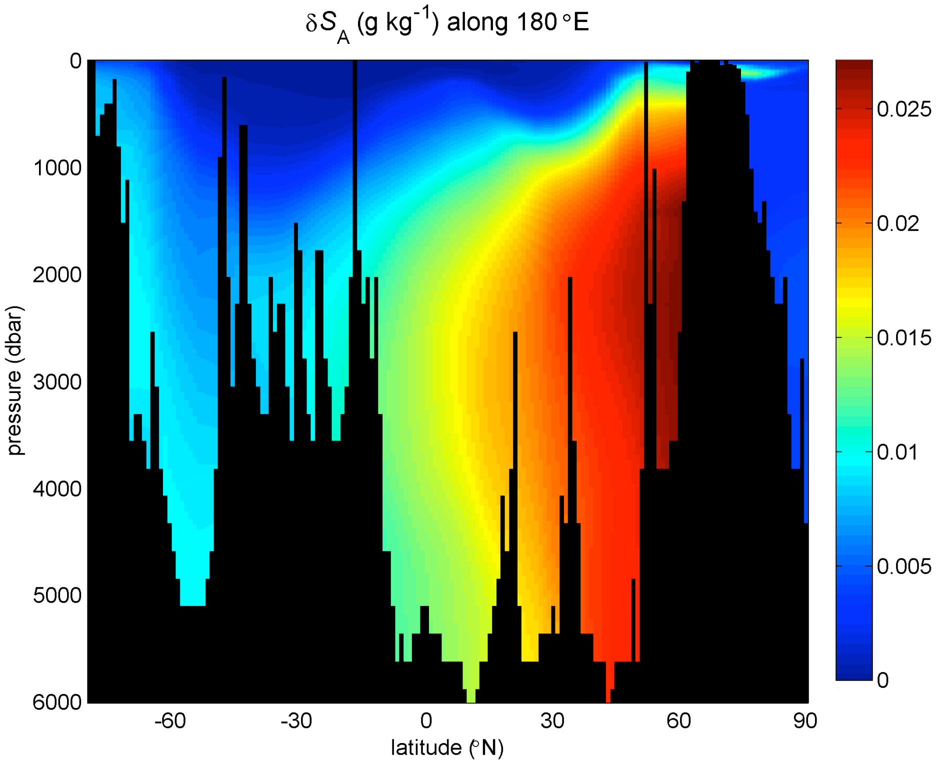


Figure 2 (b). A vertical section of Absolute Salinity Anomaly δS_{A} along 180°E in the Pacific Ocean.

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_ASal). 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.

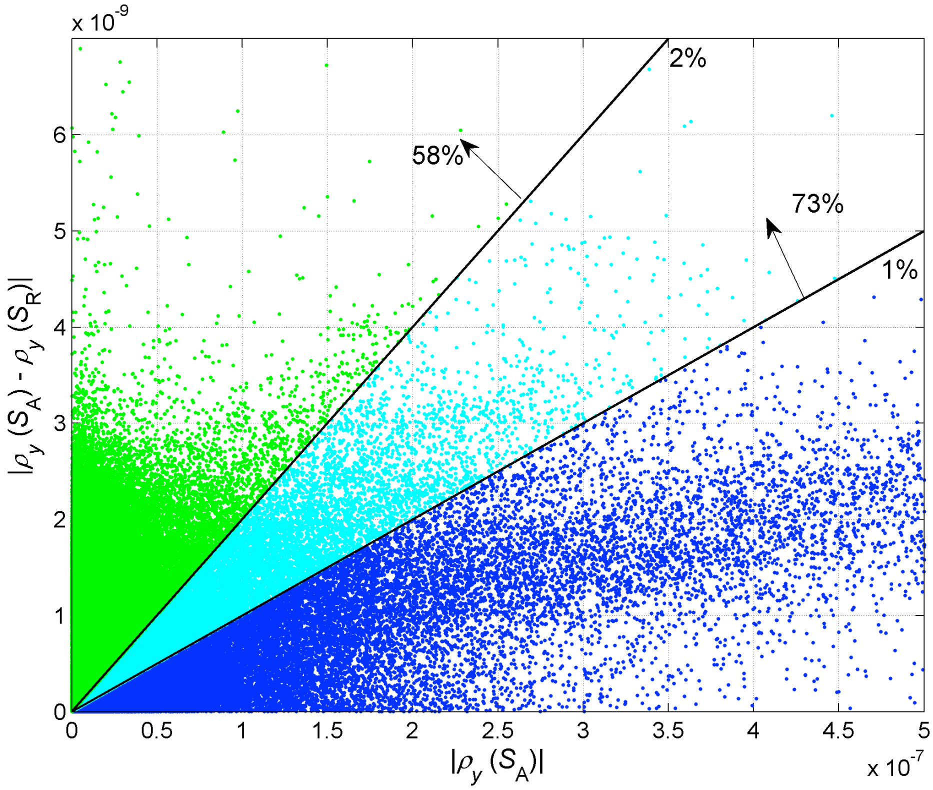


Figure A.5.1. The northward density gradient at constant pressure (the horizontal axis) for data in the global ocean atlas of Gouretski and Koltermann (2004) for $p > 1000\,\mathrm{dbar}$. The vertical axis is the magnitude of the difference between evaluating the density gradient using S_A versus S_R 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. Preformed 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. Preformed 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^{δ}) 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^{δ} to calculate Preformed Salinity S_* according to (see Eqn. (A.5.11) of appendix A.5 of the TEOS-10 Manual, IOC *et al.* (2010))

$$S_* = \frac{35.165\,04 \text{ g kg}^{-1}}{35} S_P \left(1 - r_1 R^{\delta}\right), \qquad \textit{Non-Baltic} \qquad (3)$$

where r_1 is taken to be the constant 0.35 based on the work of Pawlowicz *et al.* (2011). Note that $\left(35.165\,04 \text{ g kg}^{-1}/35\right) S_P$ 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 Preformed Salinity S_*, Reference Salinity S_R and Absolute Salinity S_A.

Figure A.4.1. Number line of salinity, illustrating the differences between Preformed 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 Preformed 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^{δ} 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, Preformed Salinity S_* in the Baltic Sea is Absolute Salinity S_A. Hence, if the observation is from the Baltic Sea, Preformed 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

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

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^{δ} is set equal to zero and **gsw_Sstar_from_SP** returns $S_* = S_R = \left(35.165\,04 \text{ g kg}^{-1}/35\right) S_P$ 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 g kg^{-1}, and the difference between Absolute Salinity and the conservative Preformed Salinity, $S_A - S_*$, is as large as 0.036 g kg^{-1}, equivalent to an increment of density of approximately 0.028 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 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 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 Θ

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 $p = 0\ \text{dbar}$ is reached. The temperature of the fluid parcel at the end of this artificial thought experiment is defined to be the potential temperature θ. Similarly, the enthalpy at the end of this artificial thought experiment is defined to be the potential enthalpy h^0, and Conservative Temperature Θ is simply potential enthalpy divided by the fixed "heat capacity" $c_p^0 \equiv 3991.867\,957\,119\,63\ \ \text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$.

Conservative Temperature Θ represents the "heat content" of seawater much more accurately than does potential temperature θ (McDougall (2003), Graham and McDougall, 2013). Θ 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 $\theta - \Theta = -1.4°\text{C}$ but is more typically no more than $\pm\,0.1°\text{C}$ (see Figure A.17.1 of IOC *et al.* (2010) which is reproduced below). To put a temperature difference of $0.1°\text{C}$ 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.

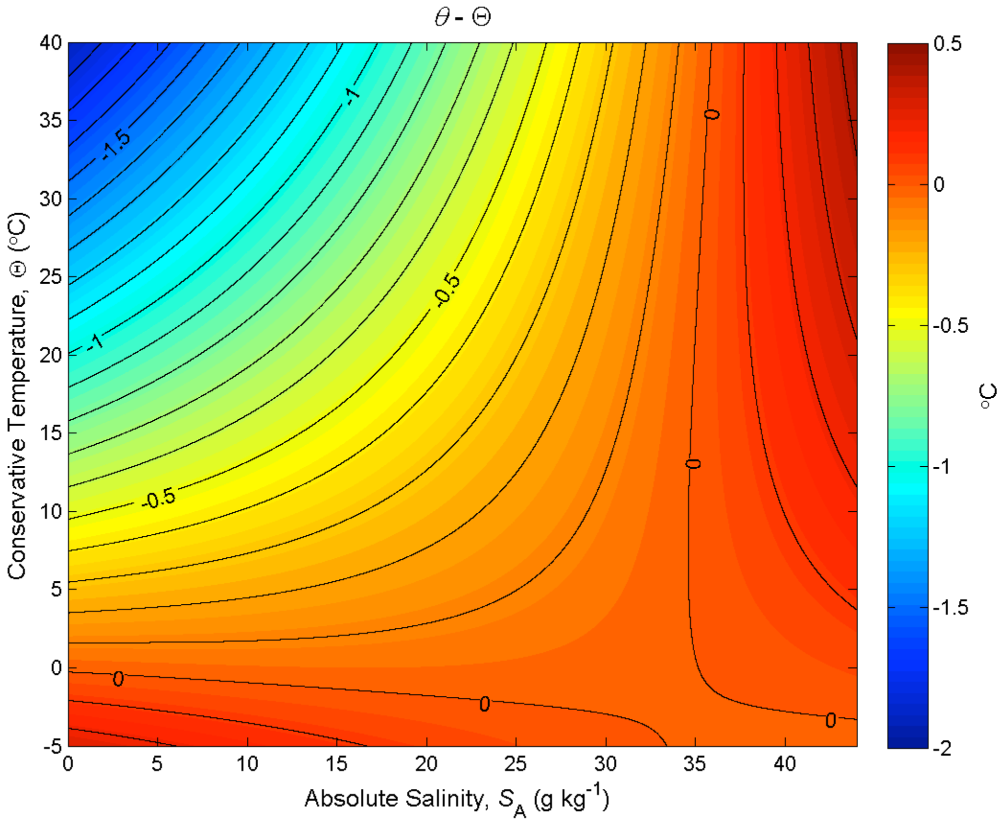


Figure A.17.1. Contours (in °C) of the difference between potential temperature and Conservative Temperature $\theta - \Theta$. This plot illustrates the non-conservative production of potential temperature θ in the ocean.

The air-sea heat flux is exactly proportional to the flux of Conservative Temperature, and because Θ is almost a perfectly conservative variable, the meridional "heat" flux is very accurately given by the meridional flux of Θ (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 Θ 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 Θ takes the place of potential temperature θ under TEOS-10.

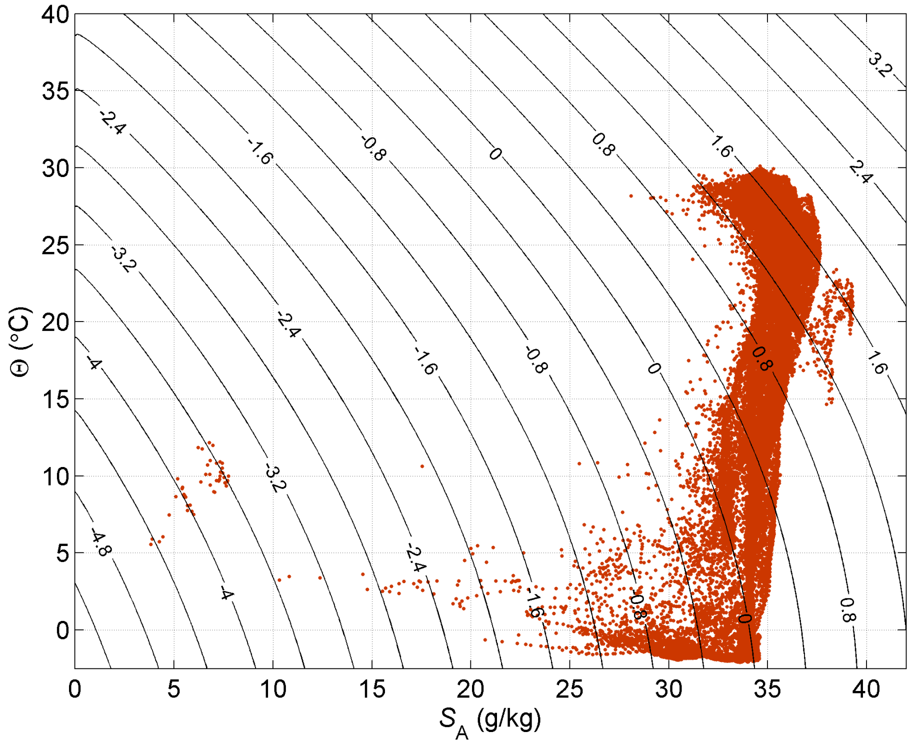


Figure A.14.1. Contours of $\left(\left|\nabla_n\theta\right|/\left|\nabla_n\Theta\right| - 1\right)\times 100\%$ at $p = 0$, showing the percentage difference between the epineutral gradients of θ and Θ. The red dots are from the global ocean atlas of Gouretski and Koltermann (2004) at $p = 0$.

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 $\left(S_{\mathrm{P}}, t, p\right)$ 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 the practice under EOS-80 regarding temperature; we archive the measured quantity, *in situ* temperature t, not the calculated quantity, potential temperature θ. 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 $\hat{v}(S_{\mathrm{A}},\Theta,p)$ for specific volume

The computationally efficient 75-term polynomial for specific volume, $\hat{v}(S_{\mathrm{A}},\Theta,p)$, 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 $(S_{\mathrm{A}}, \Theta, p)$ 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^{-1}. 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^{-1} 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^{-3}; this can be compared with the rms uncertainty of 0.004 kg m^{-3} of the underlying laboratory density data to which the TEOS-10 Gibbs function was fitted. Similarly, the appropriate thermal expansion coefficient,

$$\alpha^{\Theta} = \frac{1}{v}\frac{\partial v}{\partial \Theta}\bigg|_{S_{\mathrm{A}},p} ,$$

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 $0.03x10^{-6}\,\mathrm{K}^{-1}$, compared with the rms error of the thermal expansion coefficient of the laboratory data to which the Feistel (2008) Gibbs function was fitted of $0.73x10^{-6}\,\mathrm{K}^{-1}$. 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 α^{Θ} and β^{Θ} which are the most important aspects of the equation of state since the "thermal wind" is proportional to $\alpha^{\Theta}\nabla_{p}\Theta - \beta^{\Theta}\nabla_{p}S_{\mathrm{A}}$ and the vertical static stability is given in terms of the buoyancy frequency N by $g^{-1}N^{2} = \alpha^{\Theta}\Theta_{z} - \beta^{\Theta}(S_{\mathrm{A}})_{z}$. 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	Practical Salinity from conductivity, C (incl. for SP < 2)
gsw_C_from_SP	conductivity, C, from Practical Salinity (incl. for SP < 2)
gsw_SP_from_R	Practical Salinity from conductivity ratio, R (incl. for SP < 2)
gsw_R_from_SP	conductivity ratio, R, from Practical Salinity (incl. for SP < 2)
gsw_SP_salinometer	Practical Salinity from a laboratory salinometer (incl. for SP < 2)
gsw_SP_from_SK	Practical Salinity from Knudsen Salinity

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

gsw_SA_from_SP	Absolute Salinity from Practical Salinity
gsw_Sstar_from_SP	Preformed Salinity from Practical Salinity
gsw_CT_from_t	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	Absolute Salinity Anomaly from Practical Salinity
gsw_SA_Sstar_from_SP	Absolute Salinity & Preformed Salinity from Practical Salinity
gsw_SR_from_SP	Reference Salinity from Practical Salinity
gsw_SP_from_SR	Practical Salinity from Reference Salinity
gsw_SP_from_SA	Practical Salinity from Absolute Salinity
gsw_Sstar_from_SA	Preformed Salinity from Absolute Salinity
gsw_SA_from_Sstar	Absolute Salinity from Preformed Salinity
gsw_SP_from_Sstar	Practical Salinity from Preformed Salinity
gsw_pt_from_CT	potential temperature from Conservative Temperature
gsw_t_from_CT	in-situ temperature from Conservative Temperature
gsw_CT_from_pt	Conservative Temperature from potential temperature
gsw_pot_enthalpy_from_pt	potential enthalpy from potential temperature
gsw_pt_from_t	potential temperature
gsw_pt0_from_t	potential temperature with reference pressure of 0 dbar
gsw_t_from_pt0	in-situ temperature from potential temperature with p_ref of 0 dbar
gsw_t90_from_t48	ITS-90 temperature from IPTS-48 temperature
gsw_t90_from_t68	ITS-90 temperature from IPTS-68 temperature
gsw_z_from_p	height from pressure
gsw_p_from_z	pressure from height
gsw_z_from_depth	height from depth
gsw_depth_from_z	depth from height
gsw_Abs_Pressure_from_p	Absolute Pressure, P, from sea pressure, p
gsw_p_from_Abs_Pressure	sea pressure, p, from Absolute Pressure, P
gsw_entropy_from_CT	entropy from Conservative Temperature
gsw_CT_from_entropy	Conservative Temperature from entropy
gsw_entropy_from_pt	entropy from potential temperature
gsw_pt_from_entropy	potential temperature from entropy
gsw_entropy_from_t	entropy from in-situ temperature
gsw_t_from_entropy	in-situ temperature from entropy
gsw_adiabatic_lapse_rate_from_CT	adiabatic lapse rate from Conservative Temperature
gsw_adiabatic_lapse_rate_from_t	adiabatic lapse rate from in-situ temperature
gsw_molality_from_SA	molality of seawater
gsw_ionic_strength_from_SA	ionic strength of seawater

specific volume, density and enthalpy

gsw_specvol	specific volume
gsw_alpha	thermal expansion coefficient with respect to CT
gsw_beta	saline contraction coefficient at constant CT
gsw_alpha_on_beta	alpha divided by beta
gsw_specvol_alpha_beta	specific volume, thermal expansion and saline contraction coefficients
gsw_specvol_first_derivatives	first derivatives of specific volume
gsw_specvol_second_derivatives	second derivatives of specific volume
gsw_specvol_first_derivatives_wrt_enthalpy	first derivatives of specific volume with respect to enthalpy
gsw_specvol_second_derivatives_wrt_enthalpy	second derivatives of specific volume with respect to enthalpy
gsw_specvol_anom	specific volume anomaly
gsw_specvol_anom_standard	specific volume anomaly realtive to SSO & 0°C
gsw_rho	in-situ density and potential density
gsw_rho_alpha_beta	in-situ density, thermal expansion and saline contraction coefficients
gsw_rho_first_derivatives	first derivatives of density
gsw_rho_second_derivatives	second derivatives of density
gsw_rho_first_derivatives_wrt_enthalpy	first derivatives of density with respect to enthalpy
gsw_rho_second_derivatives_wrt_enthalpy	second derivatives of density with respect to enthalpy
gsw_sigma0	sigma0 with reference pressure of 0 dbar
gsw_sigma1	sigma1 with reference pressure of 1000 dbar
gsw_sigma2	sigma2 with reference pressure of 2000 dbar
gsw_sigma3	sigma3 with reference pressure of 3000 dbar
gsw_sigma4	sigma4 with reference pressure of 4000 dbar
gsw_cabbeling	cabbeling coefficient
gsw_thermobaric	thermobaric coefficient
gsw_enthalpy	enthalpy
gsw_enthalpy_diff	difference of enthalpy between two pressures
gsw_dynamic_enthalpy	dynamic enthalpy
gsw_enthalpy_first_derivatives	first derivatives of enthalpy
gsw_enthalpy_second_derivatives	second derivatives of enthalpy
gsw_sound_speed	sound speed
gsw_kappa	isentropic compressibility
gsw_internal_energy	internal energy
gsw_internal_energy_first_derivatives	first derivatives of internal energy
gsw_internal_energy_second_derivatives	second derivatives of internal energy
gsw_CT_from_enthalpy	Conservative Temperature from enthalpy
gsw_SA_from_rho	Absolute Salinity from density
gsw_CT_from_rho	Conservative Temperature from density
gsw_CT_maxdensity	Conservative Temperature of maximum density of seawater

International Council for Science
SCOR
Scientific Committee on Oceanic Research
IAPSO
UNESCO
IOC

Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS–10

vertical stability and interpolation

gsw_Turner_Rsubrho	Turner angle & Rsubrho
gsw_Nsquared	buoyancy (Brunt-Väisäla) frequency squared (N^2)
gsw_Nsquared_min	minimum buoyancy frequency squared (N^2)
gsw_stabilise_SA_const_t	minimally adjust SA to produce a stable water column, keeping in-situ temperature constant
gsw_stabilise_SA_CT	minimally adjusts SA & CT to produce a stable water column
gsw_mlp	mixed-layer pressure
gsw_Nsquared_lowerlimit	specified profile of minimum buoyancy frequency squared
gsw_SA_CT_interp	interpolates SA & CT to defined pressures
gsw_t_interp	interpolates in-situ temperature to defined pressures
gsw_tracer_CT_interp	interpolates a tracer & CT to defined pressures
gsw_tracer_interp	interpolates a tracer to defined pressures
gsw_IPV_vs_fNsquared_ratio	ratio of isopycnal potential vorticity to f times N^2

geostrophic streamfunctions, acoustic travel time and geostrophic velocity

gsw_geo_strf_dyn_height	dynamic height anomaly
gsw_geo_strf_dyn_height_pc	dynamic height anomaly for piecewise constant profiles
gsw_geo_strf_isopycnal	approximate isopycnal geostrophic streamfunction
gsw_geo_strf_isopycnal_pc	approximate isopycnal geostrophic streamfunction for piecewise constant profiles
gsw_geo_strf_Cunningham	Cunningham geostrophic streamfunction
gsw_geo_strf_Montgomery	Montgomery geostrophic streamfunction
gsw_geo_strf_steric_height	dynamic height anomaly divided by 9.7963 $m\ s^{-2}$
gsw_geo_strf_PISH	pressure integrated steric height
gsw_travel_time	acoustic travel time
gsw_geostrophic_velocity	geostrophic velocity

seawater and ice properties at freezing temperatures

gsw_CT_freezing	Conservative Temperature freezing temp of seawater
gsw_CT_freezing_poly	Conservative Temperature freezing temp of seawater (poly)
gsw_t_freezing	in-situ freezing temperature of seawater
gsw_t_freezing_poly	in-situ freezing temperature of seawater (poly)
gsw_pot_enthalpy_ice_freezing	potential enthalpy of ice at which seawater freezes
gsw_pot_enthalpy_ice_freezing_poly	potential enthalpy of ice at which seawater freezes (poly)
gsw_SA_freezing_from_CT	SA of seawater at the freezing temp (for given CT)
gsw_SA_freezing_from_CT_poly	SA of seawater at the freezing temp (for given CT) (poly)
gsw_SA_freezing_from_t	SA of seawater at the freezing temp (for given t)
gsw_SA_freezing_from_t_poly	SA of seawater at the freezing temp (for given t) (poly)
gsw_pressure_freezing_CT	pressure of seawater at the freezing temp (for given CT)
gsw_CT_freezing_first_derivatives	first derivatives of CT freezing temp of seawater
gsw_CT_freezing_first_derivatives_poly	first derivatives of CT freezing temp of seawater (poly)
gsw_t_freezing_first_derivatives	first derivatives of in-situ freezing temp of seawater
gsw_t_freezing_first_derivatives_poly	first derivatives of in-situ freezing temp of seawater (poly)
gsw_pot_enthalpy_ice_freezing_first_derivatives	first derivatives of potential enthalpy of ice at freezing
gsw_pot_enthalpy_ice_freezing_first_derivatives_poly	first derivatives of potential enthalpy of ice at freezing (poly)
gsw_latentheat_melting	latent heat of melting of ice into seawater

thermodynamic interaction between ice and seawater

gsw_melting_ice_SA_CT_ratio	SA to CT ratio when ice melts into seawater
gsw_melting_ice_SA_CT_ratio_poly	SA to CT ratio when ice melts into seawater (poly)
gsw_melting_ice_equilibrium_SA_CT_ratio	SA to CT ratio when ice melts, near equilibrium
gsw_melting_ice_equilibrium_SA_CT_ratio_poly	SA to CT ratio when ice melts, near equilibrium (poly)
gsw_ice_fraction_to_freeze_seawater	ice mass fraction to freeze seawater
gsw_melting_ice_into_seawater	SA and CT when ice melts in seawater
gsw_frazil_ratios_adiabatic	ratios of SA, CT and P changes during frazil ice formation
gsw_frazil_ratios_adiabatic_poly	ratios of SA, CT and P changes during frazil ice formation (poly)
gsw_frazil_properties	SA, CT & ice mass fraction from bulk SA & bulk enthalpy
gsw_frazil_properties_potential	SA, CT & ice fraction from bulk SA & bulk potential enthalpy
gsw_frazil_properties_potential_poly	SA, CT & ice fraction from bulk SA & bulk potential enthalpy (poly)

thermodynamic interaction between sea ice and seawater

gsw_melting_seaice_SA_CT_ratio	SA to CT ratio when sea ice melts into seawater
gsw_melting_seaice_SA_CT_ratio_poly	SA to CT ratio when sea ice melts into seawater (poly)
gsw_melting_seaice_equilibrium_SA_CT_ratio	SA to CT ratio when sea ice melts, near equilibrium
gsw_melting_seaice_equilibrium_SA_CT_ratio_poly	SA to CT ratio when sea ice melts, near equilibrium (poly)
gsw_seaice_fraction_to_freeze_seawater	sea ice mass fraction to freeze seawater
gsw_melting_seaice_into_seawater	SA and CT when sea ice melts into seawater

thermodynamic properties of ice Ih

gsw_specvol_ice	specific volume of ice
gsw_alpha_wrt_t_ice	thermal expansion coefficient of ice with respect to in-situ temp
gsw_rho_ice	in-situ density of ice
gsw_pressure_coefficient_ice	pressure coefficient of ice
gsw_sound_speed_ice	sound speed of ice (compression waves)
gsw_kappa_ice	isentropic compressibility of ice
gsw_kappa_const_t_ice	isothermal compressibility of ice
gsw_internal_energy_ice	internal energy of ice
gsw_enthalpy_ice	enthalpy of ice
gsw_entropy_ice	entropy of ice
gsw_cp_ice	isobaric heat capacity of ice
gsw_chem_potential_water_ice	chemical potential of water in ice
gsw_Helmholtz_energy_ice	Helmholtz energy of ice
gsw_adiabatic_lapse_rate_ice	adiabatic lapse rate of ice
gsw_pt0_from_t_ice	potential temperature of ice with reference pressure of 0 dbar
gsw_pt_from_t_ice	potential temperature of ice
gsw_t_from_pt0_ice	in-situ temp from potential temp of ice with p_ref of 0 dbar
gsw_t_from_rho_ice	in-situ temp from density of ice
gsw_pot_enthalpy_from_pt_ice	potential enthalpy from potential temperature of ice
gsw_pt_from_pot_enthalpy_ice	potential temperature from potential enthalpy of ice
gsw_pot_enthalpy_from_pt_ice_poly	potential enthalpy from potential temperature of ice (poly)
gsw_pt_from_pot_enthalpy_ice_poly	potential temperature from potential enthalpy of ice (poly)
gsw_pot_enthalpy_from_specvol_ice	potential enthalpy from specific volume of ice
gsw_specvol_from_pot_enthalpy_ice	specific volume from potential enthalpy of ice
gsw_pot_enthalpy_from_specvol_ice_poly	potential enthalpy from specific volume of ice (poly)
gsw_specvol_from_pot_enthalpy_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
gsw_SA_CT_from_sigma0_spiciness0	SA & CT from given sigma and spiciness with p_ref of 0 dbar
gsw_SA_CT_from_sigma1_spiciness1	SA & CT from given sigma and spiciness with p_ref of 1000 dbar
gsw_SA_CT_from_sigma2_spiciness2	SA & CT from given sigma and spiciness with p_ref of 2000 dbar

neutral versus isopycnal slopes and ratios

gsw_isopycnal_slope_ratio	ratio of the slopes of isopycnals on the SA-CT diagram for p & p_ref
gsw_isopycnal_vs_ntp_CT_ratio	ratio of the gradient of CT in a potential density surface to that in the neutral tangent plane
gsw_ntp_pt_vs_CT_ratio	ratio of gradients of pt & CT in a neutral tangent plane

derivatives of entropy, CT and pt

gsw_CT_first_derivatives	first derivatives of Conservative Temperature
gsw_CT_second_derivatives	second derivatives of Conservative Temperature
gsw_entropy_first_derivatives	first derivatives of entropy
gsw_entropy_second_derivatives	second derivatives of entropy
gsw_pt_first_derivatives	first derivatives of potential temperature
gsw_pt_second_derivatives	second derivatives of potential temperature

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)$^{-1}$
gsw_valence_factor	valence factor of sea salt; 1.2452898
gsw_atomic_weight	mole-weighted atomic weight of sea salt; 31.4038218... g/mol

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

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 realtive 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

Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS–10

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_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

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

gsw_specvol_t_exact	specific volume
gsw_alpha_wrt_CT_t_exact	thermal expansion coefficient with respect to Conservative Temperature
gsw_alpha_wrt_pt_t_exact	thermal expansion coefficient with respect to potential temperature
gsw_alpha_wrt_t_exact	thermal expansion coefficient with respect to in-situ temperature
gsw_beta_const_CT_t_exact	saline contraction coefficient at constant Conservative Temperature
gsw_beta_const_pt_t_exact	saline contraction coefficient at constant potential temperature
gsw_beta_const_t_exact	saline contraction coefficient at constant in-situ temperature
gsw_specvol_anom_standard_t_exact	specific volume anomaly realtive to SSO & 0°C
gsw_rho_t_exact	in-situ density
gsw_pot_rho_t_exact	potential density
gsw_sigma0_pt0_exact	sigma0 from pt0 with reference pressure of 0 dbar
gsw_enthalpy_t_exact	enthalpy
gsw_dynamic_enthalpy_t_exact	dynamic enthalpy
gsw_CT_first_derivatives_wrt_t_exact	first derivatives of Conservative Temperature with respect to t
gsw_enthalpy_first_derivatives_wrt_t_exact	first derivatives of enthalpy with respect to t
gsw_sound_speed_t_exact	sound speed
gsw_kappa_t_exact	isentropic compressibility
gsw_kappa_const_t_exact	isothermal compressibility
gsw_internal_energy_t_exact	internal energy
gsw_SA_from_rho_t_exact	Absolute Salinity from density
gsw_t_from_rho_exact	in-situ temperature from density
gsw_t_maxdensity_exact	in-situ temperature of maximum density of seawater
gsw_cp_t_exact	isobaric heat capacity
gsw_isochoric_heat_cap_t_exact	isochoric heat capacity
gsw_chem_potential_relative_t_exact	relative chemical potential
gsw_chem_potential_water_t_exact	chemical potential of water in seawater
gsw_chem_potential_salt_t_exact	chemical potential of salt in seawater
gsw_t_deriv_chem_potential_water_t_exact	temperature derivative of chemical potential of water
gsw_dilution_coefficient_t_exact	dilution coefficient of seawater
gsw_Gibbs_energy_t_exact	Gibbs energy
gsw_Helmholtz_energy_t_exact	Helmholtz energy
gsw_osmotic_coefficient_t_exact	osmotic coefficient of seawater
gsw_osmotic_pressure_t_exact	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:

gsw_gibbs	the TEOS-10 Gibbs function of seawater and its derivatives
gsw_gibbs_ice	the TEOS-10 Gibbs function of ice and its derivatives
gsw_SAAR	Absolute Salinity Anomaly Ratio (excluding the Baltic Sea)
gsw_Fdelta	ratio of Absolute to Preformed Salinity, minus 1
gsw_deltaSA_atlas	Absolute Salinity Anomaly atlas value (excluding the Baltic Sea)
gsw_SA_from_SP_Baltic	calculates Absolute Salinity in the Baltic Sea
gsw_SP_from_SA_Baltic	calculates Practical Salinity in the Baltic Sea
gsw_infunnel	“oceanographic funnel” check for the 75-term equation
gsw_entropy_part	entropy minus the terms that are a function of only SA
gsw_entropy_part_zerop	entropy_part evaluated at 0 dbar
gsw_quadprog	quadratic solver for water column stabilisation
gsw_wiggliness	amount of variation in a cast
gsw_data_interp	Barker & McDougall (2020) MR-pchip interpolation
gsw_interp_ref_cast	linearly interpolates the reference cast
gsw_linear_interp_SA_CT	linearly interpolates (SA,CT,p) to the desired p
gsw_pchip_interp_SA_CT	pchip interpolation of (SA,CT,p) to the desired p
gsw_rr68_interp_SA_CT	Reiniger & Ross (1968) interpolation of (SA,CT,p) to the desired p
gsw_spline_interp_SA_CT	spline interpolation of (SA,CT,p) to the desired p
gsw_gibbs_pt0_pt0	gibbs(0,2,0,SA,t,0)
gsw_gibbs_ice_part_t	part of gibbs_ice(1,0,t,p)
gsw_gibbs_ice_pt0	part of gibbs_ice(1,0,pt0,0)
gsw_specvol_SSO_0	specvol(35.16504,0,p)
gsw_enthalpy_SSO_0	enthalpy(35.16504,0,p)
gsw_Hill_ratio_at_SP2	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	front page to the GSW Oceanographic Toolbox
gsw_check_functions	checks that all the GSW functions work correctly
gsw_demo	demonstrates many GSW functions and features
gsw_ver	displays the GSW version number
gsw_licence	creative commons licence for the GSW Oceanographic Toolbox

The GSW Toolbox is available from

www.TEOS–10.org

8. Changes to oceanographic practice under TEOS-10

For the past thirty years, using 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 θ in order to analyze and publish water-mass characteristics on the $S_\mathrm{P} - \theta$ diagram. On this $S_\mathrm{P} - \theta$ diagram we have been able to draw curved contours of potential density using EOS-80.

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

TEOS-10 also defines a new temperature variable, Conservative Temperature Θ, which takes the place of potential temperature θ (see section 5 above). Operationally, the calculation of Conservative Temperature Θ as a function of $\left(S_\mathrm{A}, t, p\right)$ under TEOS-10 is no different in principle from the way potential temperature was calculated from $\left(S_\mathrm{P}, t, p\right)$ under EOS-80; in both cases a simple computer algorithm is called. Conservative Temperature Θ has the advantage over θ of more accurately representing the "heat content" of seawater, and is also much closer (by a factor of a hundred) to being a conservative variable than is potential temperature. Heat is exchanged between the ocean and its atmosphere and ice boundaries as a flux of potential enthalpy which is exactly $c_p^0 \equiv 3991.867\,957\,119\,63 \ \mathrm{J\,kg^{-1}\,K^{-1}}$ times the mass, times the corresponding flux of Θ. The transport of potential enthalpy $c_p^0\Theta$ in the ocean, and in particular across ocean sections, can be regarded as the transport of "heat" irrespective of whether there are non-zero fluxes of mass and/or of salt across such ocean sections (see section 3.23 of IOC *et al*., 2010).

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

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, ω-surfaces and

Neutral Density (γ^{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 ω-surfaces (Klocker *et al.* (2010)) and Neutral Density γ^{n} (Jackett and McDougall (1997)).

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

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

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

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

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

where

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

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

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

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

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

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

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

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

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

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

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

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

If an ocean model is to be run for only a short time (perhaps as long as a century) then it may be sufficiently accurate to carry only one salinity variable, namely Absolute Salinity S_{A}.

For longer integrations the neglect of the non-conservative biogeochemical source term means that the model's salinity variable S_A will depart from reality. A more detailed discussion of these points is available in appendix A.20 of IOC *et al.* (2010). To our knowledge, as of July 2020, no ocean model has adopted this approach; rather they have used only one salinity variable, namely Absolute Salinity S_A.

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

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

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

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

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

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

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

10. A guide to the GSW Oceanographic Toolbox

The key attributes of the three oceanographic variables S_A, S_* and Θ may be summarized as follows. Preformed Salinity S_* and Conservative Temperature Θ 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 $2\text{x}10^{-14}$, 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 Θ. 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 Θ, 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 $S_\mathrm{A} - \Theta$ 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 first page), headed "specific volume, density and enthalpy", are all derived from the computationally-efficient 75-term expression for specific volume, $\hat{v}\left(S_\mathrm{A},\Theta,p\right)$ 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** can be 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 Θ or S_A respectively.

The next group of functions, headed "vertical stability and interpolation", delivers variables which are defined in terms of the vertical gradients of S_A and Θ 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 interpolation functions implement the algorithms of Barker and McDougall (2020) which uses multiply rotated piecewise cubic Hermite polynomials, while the stablisation functions implement the method described by Barker and McDougall (2017).

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 Θ 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 function, **gsw_geostrophic_velocity**, 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 ω-surface (Klocker *et al.* (2010)) or a potential density surface).

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 (on page 3) 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 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 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 of GSW functions, "laboratory functions, for use with densimeter measurements", 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). Two of these three functions are also listed on the lower left group of the fourth page; they are also listed here to give them more prominence for those using a densimeter in a laboratory setting.

The group of GSW functions on the right-hand side of the third page, headed "specific volume, density and enthalpy in terms of CT, based on the exact Gibbs function" delivers the same outputs as the corresponding group on page 1, and with the same input variables. The functions on page 1 are based on the 75-term expression for specific volume, $\hat{v}\left(S_{\mathrm{A}},\Theta,p\right)$, whereas the functions on page 3 use the exact Gibbs function for seawater to calculate specific volume. The function names in this group differ from those on page 1 by the additional "_exact" at the end of each function name. These functions 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 "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 next list, headed "basic thermodynamic properties in terms of in-situ t, based on the exact Gibbs function" contains 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.

In the *documentation set* 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 $\left(S_\mathrm{P}, t, p\right)$ 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 $\left(S_\mathrm{A}, \Theta, p\right)$. With the data set in this form, water masses may be analyzed accurately on the $S_\mathrm{A} - \Theta$ 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_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_ref is given by **gsw_rho**(SA,CT,p_ref).

11. References

Barker, P. M. and T. J. McDougall, 2017: Stabilising hydrographic profiles with minimal change to water masses. *Journal of Atmospheric and Oceanic Technology*, **34**, 1935-1945.

Barker, P. M. and T. J. McDougall, 2020: Two Interpolation Methods using Multiply-Rotated Piecewise Cubic Hermite Interpolating Polynomials. *Journal of Atmospheric and Oceanic Technology*, **37**, 605-619.

Feistel, R., 2003: A new extended Gibbs thermodynamic potential of seawater, *Progr. Oceanogr.*, **58**, 43-114.

Feistel, R., 2008: A Gibbs function for seawater thermodynamics for −6 to 80 °C and salinity up to 120 g kg^{-1}, *Deep-Sea Res. I*, **55**, 1639-1671.

Feistel, R., S. Weinreben, H. Wolf, S. Seitz, P. Spitzer, B. Adel, G. Nausch, B. Schneider and D. G. Wright, 2010: Density and Absolute Salinity of the Baltic Sea 2006–2009. *Ocean Science,* **6**, 3–24. http://www.ocean-sci.net/6/3/2010/os-6-3-2010.pdf

Graham, F. S. and T. J. McDougall, 2013: Quantifying the non-conservative production of Conservative Temperature, potential temperature and entropy. *Journal of Physical Oceanography*, **43**, 838-862.

Hill, K. D., T. M. Dauphinee and D. J. Woods, 1986: The extension of the Practical Salinity Scale 1978 to low salinities, *IEEE J. Oceanic Eng.*, **11**, 109–112.

IAPWS, 2008: Release on the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater. The International Association for the Properties of Water and Steam. Berlin, Germany, September 2008, available from www.iapws.org.

IAPWS, 2009: Supplementary Release on a Computationally Efficient Thermodynamic Formulation for Liquid Water for Oceanographic Use. The International Association for the Properties of Water and Steam. Doorwerth, The Netherlands, September 2009, available from www.iapws.org. This Release is referred to in the text as **IAPWS-09**.

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. Available from www.TEOS-10.org

Jackett, D. R. and T. J. McDougall, 1997: A neutral density variable for the world's oceans. *Journal of Physical Oceanography*, **27**, 237-263.

Klocker, A., T. J. McDougall and D. R. Jackett, 2009: A new method for forming approximately neutral surfaces. *Ocean Sci.*, **5**, 155-172.

McDougall, T. J. 2003: Potential enthalpy: A conservative oceanic variable for evaluating heat content and heat fluxes. *Journal of Physical Oceanography*, **33**, 945-963.

McDougall T. J. and P. M. Barker, 2011: Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox, 28pp., SCOR/IAPSO WG127, ISBN 978-0-646-55621-5. Available from www.TEOS-10.org (this is the present document).

McDougall, T. J., D. R. Jackett, F. J. Millero, R. Pawlowicz and P. M. Barker, 2012: A global algorithm for estimating Absolute Salinity. *Ocean Science*, **8**, 1123-1134. http://www.ocean-sci.net/8/1123/2012/os-8-1123-2012.pdf

McDougall, T. J., D. R. Jackett, D. G. Wright and R. Feistel, 2003: Accurate and computationally efficient algorithms for potential temperature and density of seawater. *Journal of Atmospheric and Oceanic Technology*, **20**, 730-741.

McDougall, T. J. and A. Klocker, 2010: An approximate geostrophic streamfunction for use in density surfaces. *Ocean Modelling*, **32**, 105-117.

Millero, F. J., R. Feistel, D. G. Wright, and T. J. McDougall, 2008: The composition of Standard Seawater and the definition of the Reference-Composition Salinity Scale, *Deep-Sea Res. I*, **55**, 50-72.

Pawlowicz, R., 2010: What every oceanographer needs to know about TEOS-10 (The TEOS-10 Primer), unpublished manuscript, available from www.TEOS-10.org.

Pawlowicz, R., D. G. Wright and F. J. Millero, 2011: The effects of biogeochemical processes on oceanic conductivity/salinity/density relationships and the characterization of real seawater. *Ocean Science*, **7**, 363–387. http://www.ocean-sci.net/7/363/2011/os-7-363-2011.pdf

Roquet, F., G. Madec, T. J. McDougall and P. M. Barker, 2015: Accurate polynomial expressions for the density and specific volume of seawater using the TEOS-10 standard. *Ocean Modelling*, **90**, 29-43, http://dx.doi.org/10.1016/j.ocemod.2015.04.002

Wright, D. G., R. Pawlowicz, T. J. McDougall, R. Feistel and G. M. Marion, 2011: Absolute Salinity, "Density Salinity" and the Reference-Composition Salinity Scale: present and future use in the seawater standard TEOS-10. *Ocean Sci.*, **7**, 1-26. http://www.ocean-sci.net/7/1/2011/os-7-1-2011.pdf

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 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 g kg^{-1}, temperature in °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	g kg^{-1}	*Chlorinity* 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_SO	g kg^{-1}	35.165 04 g kg^{-1} being exactly $35\ u_\text{PS}$, corresponding to the standard ocean Practical Salinity of 35.
freezing temperatures	t^f, Θ^f	°C	*in situ* 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^{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^{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	$r = \dfrac{\alpha^{\Theta}(p)/\beta^{\Theta}(p)}{\alpha^{\Theta}(p_{\text{r}})/\beta^{\Theta}(p_{\text{r}})}$
Stability Ratio	R_ρ	1	$R_\rho = \alpha^{\Theta}\Theta_z/\beta^{\Theta}(S_{\text{A}})_z \approx \alpha^{\theta}\theta_z/\beta^{\theta}(S_{\text{A}})_z$.
isopycnal temperature gradient ratio	G^{Θ}	1	$G^{\Theta} = r\left[R_\rho - 1\right]/\left[R_\rho - r\right]; \;\; \nabla_\sigma\Theta = G^{\Theta}\nabla_n\Theta$
Practical Salinity	S_{P}	1	Defined in the range $2 < S_{\text{P}} < 42$ by PSS-78 based on measured conductivity ratios.
Reference Salinity	S_{R}	g kg^{-1}	Reference-Composition Salinity (or Reference Salinity for short) is the Absolute Salinity of seawater samples that have Reference Composition. At $S_{\text{P}} = 35$, S_{R} is exactly $u_{\text{PS}}S_{\text{P}}$. while in the range $2 < S_{\text{P}} < 42$ $S_{\text{R}} \approx u_{\text{PS}}S_{\text{P}}$.
Absolute Salinity (This is the salinity argument of all the GSW Toolbox functions.)	$S_{\text{A}} = S_{\text{A}}^{\text{dens}}$	g kg^{-1}	$S_{\text{A}} = S_{\text{R}} + \delta S_{\text{A}} \approx u_{\text{PS}}S_{\text{P}} + \delta S_{\text{A}}$ Absolute Salinity is the sum of S_{R} on the Millero *et al.* (2008a) Reference-Salinity Scale and the Absolute Salinity Anomaly. The full symbol for S_{A} is $S_{\text{A}}^{\text{dens}}$ 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 $S_{\text{A}} = S_{\text{A}}^{\text{dens}}$ is “Density Salinity”.
Absolute Salinity Anomaly	δS_{A}	g kg^{-1}	$\delta S_{\text{A}} = S_{\text{A}} - S_{\text{R}}$, the difference between Absolute Salinity, $S_{\text{A}} = S_{\text{A}}^{\text{dens}}$, and Reference-Composition Salinity. In terms of the full nomenclature of Pawlowicz *et al.* (2010), Wright *et al.* (2010b) and appendix A.4 herein, the Absolute Salinity Anomaly δS_{A} is $\delta S_{\text{R}}^{\text{dens}}$.
“Preformed Absolute Salinity”, often shortened to “Preformed Salinity”	S_*	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 *et al.* (2010), Wright *et al.* (2010b)).
“Solution Absolute Salinity”, often shortened to “Solution Salinity”	$S_{\text{A}}^{\text{soln}}$	g kg^{-1}	The mass fraction of non-H_2O constituents in seawater after it has been brought to chemical equilibrium at t = 25°C and p = 0 dbar (see Pawlowicz *et al.* (2010), Wright *et al.* (2010b)).
“Added-Mass Salinity”	$S_{\text{A}}^{\text{add}}$	g kg^{-1}	$S_{\text{A}}^{\text{add}} - S_{\text{R}}$ is the estimated mass fraction of non-H_2O constituents needed as ingredients to be added to Standard Seawater which when mixed and brought to chemical equilibrium at t = 25°C and p = 0 dbar results in the observed seawater composition.

temperature	t	ºC	
Absolute Temperature	T	K	$T/\mathrm{K} \equiv T_0/\mathrm{K} + t/(°\mathrm{C}) = 273.15 + t/(°\mathrm{C})$
temperature derivatives	T	K	When a quantity is differentiated with respect to *in situ* temperature, the symbol T is used in order to distinguish this variable from time.
Celsius zero point	T_0	K	$T_0 \equiv 273.15\ \mathrm{K}$
potential temperature	θ	ºC	Defined implicitly by Eqn. (3.1.3)
Conservative Temperature	Θ	ºC	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	J kg^{-1} K^{-1}	$c_p^0 \equiv 3991.867\,957\,119\,63\ \mathrm{J\,kg^{-1}\,K^{-1}}$. 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 Θ.
combined standard uncertainty	u_c	Varies	
enthalpy	H	J	
specific enthalpy	h	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	J kg^{-1}	specific enthalpy referenced to zero sea pressure, $h^0 = h(S_\mathrm{A}, \theta[S_\mathrm{A}, t, p, p_\mathrm{r} = 0], p_\mathrm{r} = 0)$
specific isobaric heat capacity	c_p	J kg^{-1} K^{-1}	$c_p = \partial h/\partial T\big\vert_{S_\mathrm{A},p}$
internal energy	U	J	
specific internal energy	u	J kg^{-1}	
specific isochoric heat capacity	c_v	J kg^{-1} K^{-1}	$c_v = \partial u/\partial T\big\vert_{S_\mathrm{A},v}$
Gibbs function (Gibbs energy)	G	J	
specific Gibbs function (Gibbs energy)	g	J kg^{-1}	
specific Helmholtz energy	f	J kg^{-1}	
unit conversion factor for salinities	u_PS	g kg^{-1}	$u_\mathrm{PS} \equiv (35.16504/35)\ \mathrm{g\,kg^{-1}} \approx 1.004\,715...\ \mathrm{g\,kg^{-1}}$ The first part of this expression is exact. This conversion factor is an important and invariant constant of the 2008 Reference-Salinity Scale (Millero *et al.* (2008a)).
entropy	Σ	J K^{-1}	
specific entropy	η	J kg^{-1} K^{-1}	In many other publications the symbol *s* is used for specific entropy.
density	ρ	kg m^{-3}	
density anomaly	σ^t	kg m^{-3}	$\rho(S_\mathrm{A}, t, 0) - 1000\ \mathrm{kg\,m^{-3}}$
potential density anomaly referenced to a sea pressure of 2000 dbar	σ_2	kg m^{-3}	$\rho(S_\mathrm{A}, \theta[S_\mathrm{A}, t, p, p_\mathrm{r}], p_\mathrm{r}) - 1000\ \mathrm{kg\,m^{-3}}$ where $p_\mathrm{r} = 2000\ \mathrm{dbar}$
potential density anomaly referenced to a sea pressure of 4000 dbar	σ_4	kg m^{-3}	$\rho(S_\mathrm{A}, \theta[S_\mathrm{A}, t, p, p_\mathrm{r}], p_\mathrm{r}) - 1000\ \mathrm{kg\,m^{-3}}$ where $p_\mathrm{r} = 4000\ \mathrm{dbar}$
thermal expansion coefficient with respect to *in situ* temperature	α^t	K^{-1}	$v^{-1}\partial v/\partial T\big\vert_{S_\mathrm{A},p} = -\rho^{-1}\partial\rho/\partial T\big\vert_{S_\mathrm{A},p}$
thermal expansion coefficient with respect to potential temperature θ	α^θ	K^{-1}	$v^{-1}\partial v/\partial\theta\big\vert_{S_\mathrm{A},p} = -\rho^{-1}\partial\rho/\partial\theta\big\vert_{S_\mathrm{A},p}$

thermal expansion coefficient with respect to Conservative Temperature Θ	α^{Θ}	K^{-1}	$v^{-1}\partial v/\partial\Theta\big\|_{S_{\mathrm{A}},p} = -\rho^{-1}\partial\rho/\partial\Theta\big\|_{S_{\mathrm{A}},p}$
saline contraction coefficient at constant *in situ* temperature	β^{t}	$\mathrm{kg\ g}^{-1}$	$-v^{-1}\partial v/\partial S_{\mathrm{A}}\big\|_{T,p} = \rho^{-1}\partial\rho/\partial S_{\mathrm{A}}\big\|_{T,p}$ Note that the units for β^{t} are consistent with S_{A} being in g kg^{-1}.
saline contraction coefficient at constant potential temperature	β^{θ}	$\mathrm{kg\ g}^{-1}$	$-v^{-1}\partial v/\partial S_{\mathrm{A}}\big\|_{\theta,p} = \rho^{-1}\partial\rho/\partial S_{\mathrm{A}}\big\|_{\theta,p}$ Note that the units for β^{θ} are consistent with S_{A} being in g kg^{-1}.
saline contraction coefficient at constant Conservative Temperature	β^{Θ}	$\mathrm{kg\ g}^{-1}$	$-v^{-1}\partial v/\partial S_{\mathrm{A}}\big\|_{\Theta,p} = +\rho^{-1}\partial\rho/\partial S_{\mathrm{A}}\big\|_{\Theta,p}$ Note that the units for β^{Θ} are consistent with S_{A} being in g kg^{-1}.
isothermal compressibility	κ^{t}	Pa^{-1}	
isentropic and isohaline compressibility	κ	Pa^{-1}	
chemical potential of water in seawater	μ^{W}	$\mathrm{J\ g}^{-1}$	
chemical potential of sea salt in seawater	μ^{S}	$\mathrm{J\ g}^{-1}$	
relative chemical potential of (sea salt and water in) seawater	μ	$\mathrm{J\ g}^{-1}$	$\left(\partial g/\partial S_{\mathrm{A}}\right)_{t,p} = \mu^{\mathrm{S}} - \mu^{\mathrm{W}}$
dissipation rate of kinetic energy per unit mass	ε	$\mathrm{J\ kg}^{-1}\ \mathrm{s}^{-1}$ $= \mathrm{m}^{2}\ \mathrm{s}^{-3}$	
adiabatic lapse rate	Γ	$\mathrm{K\ Pa}^{-1}$	$\Gamma = \left.\frac{\partial t}{\partial P}\right\|_{S_{\mathrm{A}},\theta} = \left.\frac{\partial t}{\partial P}\right\|_{S_{\mathrm{A}},\Theta} = \left.\frac{\partial t}{\partial P}\right\|_{S_{\mathrm{A}},\eta} = \left.\frac{\partial v}{\partial \eta}\right\|_{S_{\mathrm{A}},p} = \frac{\left(T_0+\theta\right)}{c_p^0}\left.\frac{\partial v}{\partial \Theta}\right\|_{S_{\mathrm{A}},p}$
sound speed	c	$\mathrm{m\ s}^{-1}$	
specific volume	v	$\mathrm{m}^{3}\ \mathrm{kg}^{-1}$	$v = \rho^{-1}$
specific volume anomaly	δ	$\mathrm{m}^{3}\ \mathrm{kg}^{-1}$	
thermobaric coefficient based on θ	T_{b}^{θ}	$\mathrm{K}^{-1}\mathrm{Pa}^{-1}$	$T_{\mathrm{b}}^{\theta} = \beta^{\theta}\,\partial\left(\alpha^{\theta}/\beta^{\theta}\right)/\partial P\big\|_{S_{\mathrm{A}},\theta}$
thermobaric coefficient based on Θ	T_{b}^{Θ}	$\mathrm{K}^{-1}\mathrm{Pa}^{-1}$	$T_{\mathrm{b}}^{\Theta} = \beta^{\Theta}\,\partial\left(\alpha^{\Theta}/\beta^{\Theta}\right)/\partial P\big\|_{S_{\mathrm{A}},\Theta}$
cabbeling coefficient based on θ	C_{b}^{θ}	K^{-2}	$C_{\mathrm{b}}^{\theta} = \partial\alpha^{\theta}/\partial\theta\big\|_{S_{\mathrm{A}},p} + 2\,\frac{\alpha^{\theta}}{\beta^{\theta}}\partial\alpha^{\theta}/\partial S_{\mathrm{A}}\big\|_{\theta,p} - \left(\frac{\alpha^{\theta}}{\beta^{\theta}}\right)^{2}\partial\beta^{\theta}/\partial S_{\mathrm{A}}\big\|_{\theta,p}$
cabbeling coefficient based on Θ	C_{b}^{Θ}	K^{-2}	$C_{\mathrm{b}}^{\Theta} = \partial\alpha^{\Theta}/\partial\Theta\big\|_{S_{\mathrm{A}},p} + 2\,\frac{\alpha^{\Theta}}{\beta^{\Theta}}\partial\alpha^{\Theta}/\partial S_{\mathrm{A}}\big\|_{\Theta,p} - \left(\frac{\alpha^{\Theta}}{\beta^{\Theta}}\right)^{2}\partial\beta^{\Theta}/\partial S_{\mathrm{A}}\big\|_{\Theta,p}$
buoyancy frequency	N	s^{-1}	$N^{2} = g\left(\alpha^{\Theta}\Theta_{z} - \beta^{\Theta}S_{\mathrm{A}_z}\right) = g\left(\alpha^{\theta}\theta_{z} - \beta^{\theta}S_{\mathrm{A}_z}\right)$
neutral helicity	H^{n}	m^{-3}	defined by Eqns. (3.13.1) and (3.13.2)
Neutral Density	γ^{n}	$\mathrm{kg\ m}^{-3}$	a density variable whose iso-surfaces are designed to be approximately neutral, i. e. $\alpha^{\Theta}\nabla_{\gamma}\Theta \approx \beta^{\Theta}\nabla_{\gamma}S_{\mathrm{A}}$.
Neutral-Surface-Potential-Vorticity	$NSPV$	s^{-3}	$NSPV = -g\rho^{-1}f\gamma_{z}^{\mathrm{n}}$ where *f* is the Coriolis parameter.
dynamic height anomaly	Ψ	$\mathrm{m}^{2}\ \mathrm{s}^{-2}$	$\mathrm{Pa\,m}^{3}\,\mathrm{kg}^{-1} = \mathrm{m}^{2}\,\mathrm{s}^{-2}$
Montgomery geostrophic streamfunction	Ψ^{M}	$\mathrm{m}^{2}\ \mathrm{s}^{-2}$	$\mathrm{Pa\,m}^{3}\,\mathrm{kg}^{-1} = \mathrm{m}^{2}\,\mathrm{s}^{-2}$

PISH (Pressure-Integrated Steric Height)	Ψ'	kg s^{-2}	streamfunction for f times the depth-integrated relative mass flux, see Eqns. (3.31.1) – (3.31.5).
Coriolis parameter	f	s^{-1}	$1.458\,42 x 10^{-4} \sin\phi$ s^{-1}, where ϕ is latitude
molar mass of Reference Seawater	M_S	g mol^{-1}	M_S is the mole-weighted average atomic weight of the constituents of Reference Seawater, $M_\mathrm{S} = 31.403\,821\,8...$ g mol^{-1}, from Millero *et al.* (2008a).
molality of seasalt in Reference Seawater	m_SW	mol kg^{-1}	$m_\mathrm{SW} = \sum_i m_i = \frac{1}{M_\mathrm{S}} \frac{S_\mathrm{A}}{(1-S_\mathrm{A})}$. 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 *et al.* (2008a)).
ionic strength of Reference Seawater	I	mol kg^{-1}	$I = \tfrac{1}{2} m_\mathrm{SW} Z^2 = \tfrac{1}{2} \sum_i m_i Z_i^2$ $= 0.622\,644\,9\ m_\mathrm{SW}$ $\approx \frac{0.622\,644\,9}{0.031\,403\,821\,8} \mathrm{mol\ kg^{-1}} \frac{S_\mathrm{A}}{(1-S_\mathrm{A})}$. m_i is the molality of constituent i in Reference Seawater.
osmotic coefficient	ϕ	1	$\phi(S_\mathrm{A},T,p) = \frac{g(0,t,p) - \mu^\mathrm{W}(S_\mathrm{A},t,p)}{m_\mathrm{SW} R (T_0 + t)}$ where the molar gas constant, $R = 8.314\,472$ J mol^{-1} K^{-1}. See also Eqns. (2.14.1) and (3.40.9) for an equivalent definition of ϕ.

Acknowledgements

We gratefully acknowledge Australian Research Council support through grant FL150100090. The authors also acknowledge financial support from CSIRO during the early development of the GSW Oceanographic Toolbox.

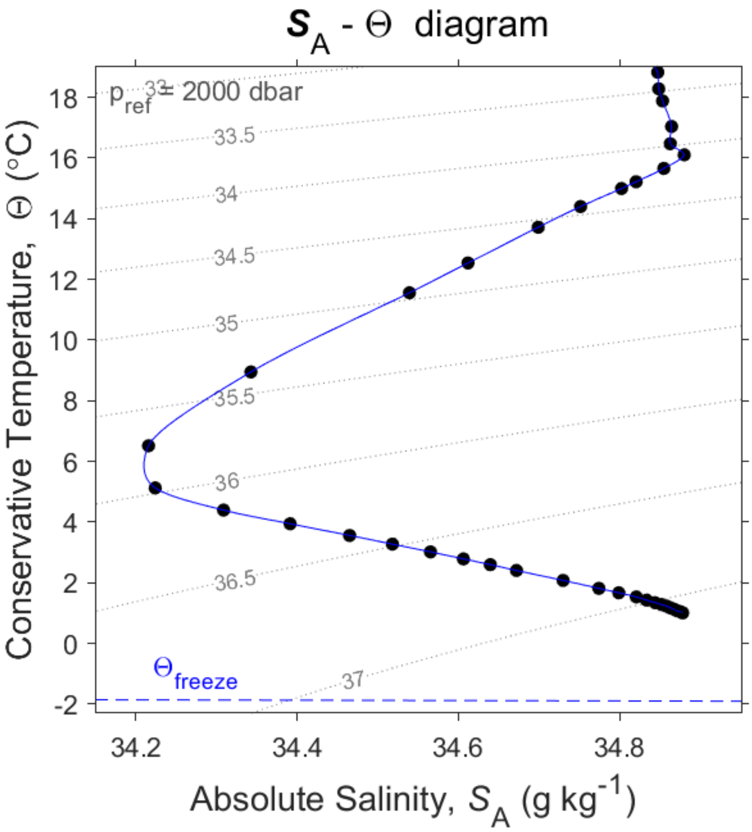
TEOS-10 and GSW in a nutshell

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 Θ, as follows,

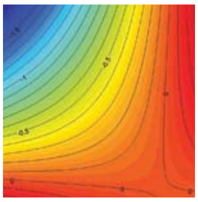
Step 1. calculate Absolute Salinity, S_A = **gsw_SA_from_SP**(SP, p, long, lat),

Step 2. calculate Conservative Temperature, Θ = **gsw_CT_from_t**(SA, t, p).

Having converted (S_P, t, p) to $(S_\mathrm{A}, \Theta, p)$, 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 $S_\mathrm{A} - \Theta$ diagram is the new "T-S" diagram. The above $S_\mathrm{A} - \Theta$ diagram was plotted using **gsw_SA_CT_plot**. The σ_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). In the above diagram the raw data appears as black dots and the blue line was produced using the function **gsw_SA_CT_interp.**



www.TEOS-10.org