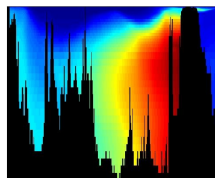


TEOS-10 PRIMER



What every oceanographer needs to know about TEOS-10
(The TEOS-10 Primer)

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Oct 2010, last updated April 2013 (v8)

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1 Introduction and FAQ

- **What is TEOS-10?**

In 2010, the Intergovernmental Oceanographic Commission (IOC), International Association for the Physical Sciences of the Oceans (IAPSO) and the Scientific Committee on Oceanic Research (SCOR) jointly adopted a new standard for the calculation of the thermodynamic properties of seawater. This new standard, now also endorsed by the International Union of Geodesy and Geophysics (IUGG), is called TEOS-10 and supercedes the old EOS-80 standard which has been in place for 30 years. It should henceforth be the primary means by which the properties of seawater are estimated. TEOS-10 was the main product of SCOR/IAPSO Working Group 127 (Thermodynamics and Equation of State of Seawater) and the Seawater Subcommittee of the International Association for the Properties of Water and Steam (IAPWS). It is now maintained by a permanent group, the Joint SCOR/IAPSO/IAPWS Committee on the Properties of Seawater (JCS).

- **Why was it adopted?**

There are many important advantages and improvements incorporated into TEOS-10. This standard

1. provides a complete thermodynamically consistent representation of all thermodynamic properties of seawater, and
2. explicitly considers the chemical composition of seawater, and incorporates corrections for composition anomalies, which will also greatly improve our knowledge and understanding of ocean circulation, and the ways in which this is modelled,
3. should lead to the opening of new research areas associated with the fundamental parameters of seawater, and
4. will facilitate development of salinity measurement technologies with better long-term stability and SI-traceability, required to investigate, e.g., climate change issues.

However, it is true that for most oceanographers, especially those not intimately concerned with precise measurements of deep ocean waters, these advantages will not be immediately apparent. They are there nonetheless!

- **How will I be affected?**

One aspect of the new standard that will immediately affect everyone is that salinity will no longer be described using the old unit-less “Practical Salinity” S_P , as defined by the Practical Salinity Scale 1978 (PSS-78). Instead, we will now speak of “Absolute Salinity”, denoted by S_A , which will have units of g kg^{-1} (i.e. a true mass fraction).

The Absolute Salinity (capitalized) used in TEOS-10 is a precisely defined measure of absolute salinity (lower case). This latter term generically refers to any salinity measure that has mass fraction units. Numerically, the S_A of a seawater sample represents, to the best available accuracy (and with certain caveats), the mass fraction of dissolved solute in so-called Standard Seawater with the same density as that of the sample. It is sometimes also referred to as “Density Salinity”, denoted S_A^{dens} . Standard Seawater (or SSW) is seawater with a particular composition, obtained from a reference material (IAPSO Standard Seawater) by adding pure water or removing pure water by evaporation. Most laboratory measurements of seawater properties are made using SSW.

However, the relative chemical composition of real seawater can differ slightly from that of SSW. It is because of these changes in relative composition that different measures of absolute salinity are possible. The numerical differences between a number of different absolute salinity measures of the same North Pacific seawater are given in Table 1. This example shows the largest variations expected in the open ocean. Note that these differences are all much larger than the precision with which we can measure S_P , which is typically ± 0.002 .

It is important to emphasize that the correct salinity argument used in the equations making up TEOS-10 is S_A , and not any other measure of absolute salinity, and DEFINITELY NOT the Practical Salinity S_P . If you

use numerical values that represent S_P as the argument in calculations using TEOS-10 functions, you will get the wrong answer!

- **What should I do to start using TEOS-10?**

All of the details behind the new standard are explained in the TEOS-10 manual (IOC et al., 2010), which is available from www.teos-10.org (and other places). The manual is 200 pages long, and almost every page is dense with thermodynamics, partial differential equations, long lists of numbers and other intimidating arcana. How should one deal with this? The first piece of advice to keep in mind is

DON'T PANIC

Basic operational procedures are straightforward. **The most important thing to do is to make sure the notation you use is consistent and correct!** In order to avoid confusion, Practical Salinity should henceforth be reported with the symbol S_P and Absolute Salinity with the symbol S_A (italicized S , upright A or P).

In the rest of this primer, the basic procedure to be followed is outlined, followed by a brief outline of the theory behind TEOS-10. References are given to particular papers in the literature, which themselves are incorporated (somewhere!) in the TEOS-10 manual.

| Salinity Measure | Definition | value | difference from S_R |
|--|--|---------------------------|-----------------------|
| S_P (Practical Salinity) | Conductivity with temperature and pressure-dependence removed (PSS78) | 34.836 | -0.164 |
| S_R (Reference Salinity) | Mass fraction of solute in SSW with the same conductivity as the sample | 35.000 g kg ⁻¹ | - |
| S_* (Preformed Salinity) | Mass fraction of solute in SSW of the same chlorinity as the sample ^a | 34.993 g kg ⁻¹ | -0.007 |
| S_A^{dens} (Density Salinity), also S_A (Absolute Salinity) | Mass fraction of solute in SSW of the same density as the sample | 35.020 g kg ⁻¹ | +0.020 |
| S_A^{soln} (Solution Salinity) | Mass fraction of solute in the sample | 35.034 g kg ⁻¹ | +0.034 |
| S_A^{add} (Added-Mass Salinity) | S_* plus mass of solid added in, e.g., laboratory experiments ^b | 35.016 g kg ⁻¹ | +0.016 |

^a In coastal areas S_* is also conservative, but may not be related to chlorinity.

^b S_A^{add} differs from S_A^{soln} because of chemical reactions involving H_2O that occur after addition; thus mass of solute may not be the same as mass of added solid. In this oceanic example the mass of solid added to SSW is inferred from knowledge of the biogeochemical processes (Pawlowicz et al., 2011)

Table 1: Different measures of salinity for water from the deep North Pacific, where composition anomalies in the open ocean are largest relative to SSW (from Wright et al., 2011). Water has been normalized to $S_R = 35.000$ g kg⁻¹. For this water the density anomaly $\delta\rho_R = 0.015$ kg m⁻³. The density anomaly is the difference between the true density and the density evaluated using S_R as the salinity argument in the TEOS-10 Gibbs function, i.e., ignoring the effects of composition variations. Note that for seawater samples with the composition of SSW all of these measures (except for Practical Salinity) are identical and equivalent. Additional definitions are also possible, but have not been explored (e.g., a measure that provides the correct ionic strength for anomalous seawater).

2 How to use TEOS-10

2.1 Data processing

At present, most conductivity-measuring oceanographic instruments report data that is converted to, and calibrated using, Practical Salinity S_P . **This will not change.** In fact S_P will continue to be the primary salinity value stored in archives (S_P is then best thought of as a conductivity measure with the temperature and pressure dependencies removed). **DO NOT ARCHIVE S_A !** However, for all other purposes S_A according to the TEOS-10 definition is required. Determining S_A involves only 3 steps:

1. Determine PSS-78 Practical Salinity S_P as before (this standard is also part of TEOS-10, albeit modified to use the modern standard for temperature, ITS-90).
2. For waters in the “Neptunian” range (i.e. $2 < S_P < 42$, $-2^\circ\text{C} < t < 35^\circ\text{C}$), a REFERENCE SALINITY S_R on the REFERENCE COMPOSITION SALINITY SCALE can be estimated as

$$S_R/(\text{g kg}^{-1}) = \frac{35.16504}{35} \times S_P \quad (1)$$

Clearly, this conversion will be important to any measurements reporting (or requiring) a precision of better than 1 g kg^{-1} . Details of the Reference Composition and the associated Reference Composition Salinity Scale are provided by Millero et al., (2008).

The Reference Salinity is the mass fraction of solute in an artificial seawater with a precisely defined Reference Composition. However, actually constructing such an artificial water is very difficult. In fact, IAPSO Standard Seawater (the current standard for calibration) can be thought of as the best physical realization of this definition. When diluted or concentrated by the addition or removal of pure water, the resulting seawater of fixed relative composition is denoted SSW. The S_R of a seawater sample is then the best available approximation of the mass fraction of solute in SSW with the same conductivity as that of the sample.

3. Because the composition of seawater is not exactly constant (there are changes in carbon system parameters, nutrients, and some other constituents like calcium, in amounts that make a practical difference at the level of accuracy we are interested in), this Reference Salinity will not be exactly the same as the actual Absolute Salinity. Instead, they differ by a small correction factor δS_A :

$$S_A = S_R + \delta S_A \quad (2)$$

This correction factor is usually but not always positive, because composition anomalies tend to be relatively uncondusive for their mass compared with “sea salt”. It can be as large as 0.02 g kg^{-1} in the open ocean, and as much as 0.09 g kg^{-1} in some coastal areas. It is therefore important when dealing with any measurements reporting a precision of better than about 0.1 g kg^{-1} .

There are several possible ways to estimate the correction factor δS_A . In order from simplest to most complex:

- (a) One can simply assume, in the absence of other information, that $\delta S_A = 0$.

This approach is probably the appropriate choice when working in coastal regions (that is, on the continental shelf and inshore) and/or in marginal seas, especially shallow seas, that have had no direct anomaly measurements (Red Sea, Mediterranean, perhaps Arctic).

Note that ignoring this correction is roughly equivalent to using the old PSS78/EOS80 approach, although even in this mode TEOS-10 provides estimates of more parameters, over a wider range in temperature, salinity, and pressure, with slightly better accuracy, than the old approach.

- (b) In the open ocean (Atlantic, Pacific, Indian, Southern Oceans, also Baltic), there exists a global atlas of δS_A . As described by McDougall et al., (2012), existing measurements were extrapolated over the whole basin by using spatially-varying correlations with concentrations of silicic acid ($Si(OH)_4$). This

is possible because the actual composition variations arising from biogeochemical processes are themselves correlated.

This is probably the appropriate choice for most “blue-water” work. The atlas itself is contained in a MATLAB code base. When using this approach, however, it would be important to state the version number of the atlas used, as the size of the corrections may change as more direct density measurements are made in different parts of the ocean and the extrapolations are made more accurately.

- (c) If measurements of carbon system parameters (two of DIC , TA , pH , or fCO_2), as well as measurements of silicate and nitrate are available, then δS_A can be estimated from a simple equation, linear in $[TA]$, DIC , $[NO_3^-]$, and $[Si(OH)_4]$. The coefficients of this equation (and the theoretical basis of the numerical model from whose calculations they are derived) are described in Pawlowicz et al., (2011).

This model-based procedure can be used anywhere in the ocean, and may also be useful in numerical models, especially those that include biogeochemical processes. This approach replicates the purely empirical data-based atlas approach to within $\pm 0.004 \text{ g kg}^{-1}$, which is approximately the error of the direct measurements used in creating the atlas. It is not clear right now which of the two approaches is more accurate. It may be simplest to rely on the atlas until more experience is obtained with these procedures.

- (d) One can make estimates of the salinity anomaly by making direct measurements of the density anomaly. The density anomaly $\delta\rho_R$ is the difference between the true density, and that computed using S_R as the salinity argument in TEOS-10 (i.e., ignoring the effects of anomalies). Then

$$\delta S_A / (\text{g kg}^{-1}) \approx \delta\rho_R / (\text{kg m}^{-3}) / 0.7519 \quad (3)$$

This may be necessary to obtain the most accurate results in areas of unknown composition anomalies, and the global database of such measurements should increase over time. However, it is unlikely that making density measurements will be necessary (or desirable) for most routine work.

4. In certain specialized applications, other definitions of absolute salinity (see Table 1) may be useful. As a practical matter, the correction factors required to convert between these different measures of absolute salinity and S_R can be approximately determined by a simple scaling of δS_A . For details, see Pawlowicz et al., (2011) and appendix A.4 of IOC et al., (2010).

2.2 Data Analysis

For almost all purposes in which observational data is analyzed the Absolute Salinity S_A is the appropriate salinity variable. Modellers may sometime be more comfortable with the conservative Preformed Salinity S_* .

In situations where turbulent mixing processes are being examined either implicitly or explicitly, the appropriate temperature variable is Conservative Temperature, because it is designed to be a “heat” variable conserved under both adiabatic mixing and changes in depth (neither in-situ nor potential temperature is conservative under both constraints, see Section 4.3). Thus Conservative Temperature (Θ) should be used for most applications in which the oceanic general circulation is being studied. This includes situations where salinity/temperature plots are used to determine the characteristics of water masses and their mixtures. Conservative Temperature is a function of Absolute Salinity, in-situ temperature, and pressure.

However, in cases where molecular diffusion or sensible conduction processes dominate (e.g., in studies of double-diffusion, or air-sea interaction), the appropriate temperature variable is still the in-situ temperature. This is because fluxes driven by these mechanisms are proportional to gradients in in-situ temperature, and not to gradients in heat content.

2.3 Reporting Measurements/Publication

In order to prevent confusion, and to facilitate future comparison, it is very important that in published work you use the CORRECT NOTATION for the salinity definition you are using, and that you document the EXACT METHOD used for estimating δS_A . In practice, this means four things:

1. DO NOT use the single word “salinity” except in cases where no numerical value is implied. Traditionally this term has been used loosely for both precise numerical values obtained using the Practical Salinity Scale-1978 as well as many other definitions related to the solute in seawater, or even in the vague sense of dissolved material. Using this ambiguous term in places where precision is needed leads to needless confusion. Instead use the full terms “Absolute Salinity”, “Practical Salinity” etc. for all TEOS-10 variables (as in Table 1). These terms are capitalized to emphasize that they specifically refer to TEOS-10 definitions as there are other ways of defining “absolute salinity”. Similarly, Conservative Temperature is also capitalized to emphasize its precise definition under TEOS-10.
2. The correct symbolic notation for TEOS-10 salinities requires an italicized S with roman subscripts and/or superscripts, e.g., S_A . This follows the general SI convention that italic type is used for quantities and variables, but roman type is used for descriptive terms and modifiers (Thompson and Taylor, 2008). The correct subscript should be used in all cases where specific numerical values are discussed.
3. Since TEOS-10 salinities now represent mass fractions of solute under different definitions, appropriate units should be associated with numerical values (e.g., on figure axis labels). Usually these would be g kg^{-1} so that numerical values are close to traditional numerical values for the salinity of particular parcels of seawater. However, in some cases other units may be used. For example, if the freshwater fraction of seawater is written as $(1 - S_A)$ then Absolute Salinities should be in kg kg^{-1} , where

$$S_A/(\text{g kg}^{-1}) = 1000 \times S_A/(\text{kg kg}^{-1}) \quad (4)$$

This “quantity equation” uses the general SI convention that unit specifiers can be multiplied or divided as if they were variables (Thompson and Taylor, 2008). Under this convention the freshwater fraction would be defined unambiguously as $(1 - S_A/(\text{kg kg}^{-1}))$.

4. In your “methods” section (or elsewhere as deemed useful) you should have a sentence similar to: “Salinities are reported on the TEOS-10 Absolute Salinity scale (IOC et al., 2010) with δS_A taken from version 3.0 of the McDougall et al., (2012) database” (modified as appropriate if another method for δS_A is being used).

3 What are the advantages and disadvantages of TEOS-10?

3.1 Advantages

1. **Use of mass fraction**

In TEOS-10, the explicit scaling which in the definition of Practical Salinity maintained continuity with the old salinity measures based on Knudsen titration for chlorinity is modified in order to have the best available measure of mass fraction. Salinities in TEOS-10 are reported as true mass fractions, consistent with practices in other scientific fields.

2. **Use of latest temperature standards**

EOS80 calculations require temperature on the old IPTS-68 scale, but for 20 years now temperatures have been calibrated and reported on the newer ITS90 scale, necessitating awkward corrections. This is no longer necessary in TEOS-10.

3. **A thermodynamically consistent description of seawater**

Properties like (e.g.,) the density, sound speed, and heat capacity are related to one another through thermodynamic relationships, but the EOS80 equations are inconsistent with these relationships. TEOS-10 is constructed in such a way that all thermodynamic relationships are consistent.

Also, the use of TEOS-10 allows for the calculation of thermodynamically important variables such as the enthalpy, internal energy, and entropy. These variables were not available from EOS80. Their calculation will allow heat fluxes and heat budgets to be more accurately determined.

4. **Use of the latest, best measurements of water properties over a much wider range of temperature, pressure, and salinity**

The best and most recent measurements of pure water and for seawater are included, as are the latest values for atomic weights (whose present uncertainty alone leads to an uncertainty of about 0.001 g kg^{-1} in the absolute salinity).

5. **More accurate values for seawater properties**

This is especially true when salinities are corrected for composition variations.

6. **Standardizes a composition model for seawater**

The definition of a Reference Composition (i.e. a complete breakdown of the major ionic constituents in an artificial seawater) forms a baseline to which compositional variations can be compared.

3.2 Disadvantages

Although there are substantial advantages to using TEOS-10, the price to be paid for this is that the mathematical equations making up this standard are rather complex and involve many coefficients specified to 16 significant digits. It is NOT RECOMMENDED that you try to programme these yourself. Instead, you should use software developed by members of SCOR/IAPSO WG127. Currently this software is available in MATLAB, C, FORTRAN, and Visual Basic at www.teos-10.org. At present there is no easy way to use TEOS-10 if you are limited to, e.g., Excel.

4 Brief theory behind TEOS-10

4.1 Utility of the Gibbs function

The basis for TEOS-10 is the construction of a Gibbs function. The Gibbs function (named after Josiah Willard Gibbs, b1839-d1903) is a THERMODYNAMIC POTENTIAL FUNCTION (TPF). A TPF is a scalar function used to represent the thermodynamic state of a system. One great advantage of the Gibbs function as a description of a system is that all thermodynamic properties of the system can be determined by specific combinations of derivatives of that function. For example, the density ρ , sound speed c , specific heat capacity c_p , specific entropy η , and specific enthalpy h are:

$$\rho = (g_P)^{-1} \quad (5)$$

$$c = g_P \sqrt{g_{TT} / (g_{TP}^2 - g_{TT}g_{PP})} \quad (6)$$

$$c_p = -Tg_{TT} \quad (7)$$

$$\eta = -g_T \quad (8)$$

$$h = g - Tg_T \quad (9)$$

where the Gibbs function $g = g(S_A, t, P)$ is an empirical function of absolute salinity, temperature and pressure, and $g_X = \partial g / \partial X$, holding all other variables constant. $T = T_0 + t$ is the absolute temperature of the system ($^{\circ}\text{K}$), with t the temperature in $^{\circ}\text{C}$ and $T_0 \equiv 273.15$.

The Gibbs function thus represents a theoretical tool by which measurements of all thermodynamic properties of SSW can be combined into a single fit. This single fit will in turn be consistent with all the measurements, and will provide a thermodynamically consistent representation that will interpolate between the measurements. The TEOS-10 fit is described by Feistel (2008).

4.2 Meaning of the Gibbs function

However, the Gibbs function also has a deeper meaning, which is of fundamental importance to understanding the energy or “heat” budget of the oceans. First, it is necessary to consider two important thermodynamic parameters. These are h , the SPECIFIC ENTHALPY, and η , the SPECIFIC ENTROPY of the system. In this context, “specific” implies a measure per unit mass.

The specific enthalpy is defined as the sum of two terms:

$$h \equiv u + P\nu \quad (10)$$

where u is the specific internal energy of the system (i.e. the kinetic energy involved in vibrating molecules plus the potential energy of chemical bonds and electrostatic charges), and $P\nu$ is the energy required to make room for the system by displacing its environment. Here P is the pressure of the system and ν is the specific volume ($=1/\rho$). The specific enthalpy is therefore a measure of the heat content of the system.

Entropy measures the amount of disorder in the system, or the nonmechanical energy which is not accessible. It has the special property that it is always produced (rather than destroyed) by both molecular and turbulent mixing processes. Both entropy and enthalpy can themselves be calculated from the Gibbs function (eqs. 8-9).

The fundamental thermodynamic relation between small changes in enthalpy, internal energy, and entropy is

$$dh - \nu dP = du + P d\nu = T d\eta + \mu dS_A \quad (11)$$

from which we see that

1. a change in pressure dP by itself alters the specific enthalpy of a seawater parcel,
2. the work done in compressing (changing the volume) of a seawater parcel $P d\nu$ changes its internal energy, while

3. changes dS_A in the Absolute Salinity of the parcel result in changes in entropy $d\eta$, through a CHEMICAL POTENTIAL μ (which itself can also be derived from the Gibbs function).

The Gibbs function g is formally defined as

$$g \equiv h - T\eta \quad (12)$$

and is therefore a measure of the maximum energy available to do nonmechanical work (like stirring or mixing) in an isothermal, adiabatic system. However, the ocean is not isothermal. As different water masses mix, changes in temperature and salinity will occur, and hence energy is converted from one form to another. The concept of conservation of energy thus becomes critical to fully understanding ocean circulation.

Energy conservation is quantified by the First Law of Thermodynamics. Both entropy and enthalpy are key thermodynamic variables that are involved in the First Law. Although a proper derivation of the First Law in a fluid system with added solute is complicated (for details, see Appendix B of IOC et al., 2010), the result shows that the convergence of the radiative and molecular fluxes of heat as well as the dissipation of turbulent kinetic energy both act to “warm” a fluid parcel (actually, increase its enthalpy).

However, in the ocean the energy contribution from the dissipation of kinetic energy is typically small. Thus, when seawater undergoes turbulent mixing at any given pressure, away from direct radiation, enthalpy is almost exactly conserved. As a result of the “contraction on mixing” (the cabbeling effect on ν that arises because of the curvature of isopycnals on a temperature-salinity diagram) internal energy will increase (c.f. eqn. 11). Entropy also increases irreversibly as a result of mixing. These properties, namely that enthalpy is a conservative variable under the process of turbulent mixing at a fixed pressure while entropy is not, make these parameters fundamentally important to our understanding of how the ocean transports and diffuses “heat”.

4.3 Conservative Tracers for “Heat Content” and Salt

Although the temperature and Absolute Salinity are required as arguments to the TEOS-10 Gibbs function, we are also interested in deriving conservative tracers in the ocean. In this context, “conservative” describes a tracer whose quantity in a specified volume of seawater stays constant, in the absence of fluxes through the boundaries of that volume (over time, while it mixes, etc.).

The true heat content of the system is not simply related to the average temperature. Instead it is most rigorously identified with the enthalpy, which as we have explained above is not affected by turbulent mixing. However, the enthalpy is affected by the ambient pressure. In the same way that pressure effects are removed from in situ temperature in the definition of potential temperature (by moving the sample without a heat flux to or mass exchange with its surroundings to a reference pressure which we take to be the pressure at the water’s surface), the pressure effect can be removed from enthalpy to create a POTENTIAL ENTHALPY h_0 as a measure of heat content. Note that the word “potential” has yet another implication here than as it is used in the name TPF or in the name of μ .

Potential enthalpy is then an ideal conservative variable for heat content. It can be scaled into a new variable, CONSERVATIVE TEMPERATURE, denoted Θ .

$$\Theta = \frac{h_0}{c_p^0} \quad (13)$$

The scale factor c_p^0 is a constant carefully chosen so that potential temperature θ and Conservative Temperature Θ will be numerically similar for typical seawaters at $S_P = 35$, or near $t = 0^\circ\text{C}$. However, the difference between the two can exceed 1°C when salinities are low and temperatures high (for details, see IOC et al., 2010).

In addition, it would be useful to have a conservative tracer for salinity. The Absolute Salinity S_A is not conservative, because it slowly increases in the ocean due to biogeochemical processes, which remineralize carbon and nutrients. The Reference Salinity S_R is also not conservative, since it is measured with conductivity which will also slowly increase due to these increases in concentrations of nutrient and carbon system ions. However, we can “remove” these effects and construct a conservative salinity tracer S_* . Typically this PREFORMED SALINITY S_* will equal S_R (and S_A) in SSW, but as ions are added it will become smaller than either S_R and S_A (as illustrated by the example in Table 1).

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