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Research article

The absolute seawater entropy: Part I. Definition

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Abstract. The absolute entropy of seawater is defined as an improved version of the relationship defined by Millero in 1976 and 1983. The first improvements concern the complex non-linear dependence of entropy on pressure, temperature and salinity, with the use of the standard TEOS10 formulation based on a fit of the oceanic Gibbs function to more recent observations. On the other hand, more recent thermodynamic tables have been used to increase the accuracy of the Millero's salinity increment to this standard formulation, to deduce the absolute version of entropy with new values for the pure-water and sea-salts absolute reference entropies. The differences between the values of the seawater entropy calculated with the Millero and TEOS10 formulations (standard and absolute) are documented, before a more complete study shown in the second part of the paper of the absolute seawater entropy computed from observed vertical profiles and analysed surface datasets.

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1. Introduction

The absolute entropy of the moist-air atmosphere was first defined by Hauf and Höller [1987], but was never calculated or studied for its own sake until recently¹. Similarly, the absolute entropy of sea-salt oceans has already been defined in the papers by Millero and Leung [1976] and Millero [1983], recalled in Sharqawy et al. [2010b] and Qasem et al. [2023] but not in Nayar et al. [2016], without attempt until now to calculate it from in-situ measurements or from numerical model outputs.

These “absolute” definitions of the entropies of the atmosphere and the ocean are obtained from the reference values of entropies available in all thermodynamic and thermochemical tables², this for the various species N_2 , O_2 , Ar , CO_2 and H_2O making up the moist-air atmosphere, and liquid water, Na^+ , Mg^{2+} , ..., Cl^- , SO_4^{2-} , ... for the seasalt ocean.

These absolute reference values have been computed by applying the third law of thermodynamics, which, following the works of Nernst [1906] and then Planck [1911, 1917], stipulates that: the entropies of the most stable crystalline state of all bodies cancel out at the absolute zero of temperature. This

¹ In the studies of Marquet [2011, 2014], Marquet and Geleyn [2015], Marquet [2017], Marquet and Dauhut [2018], Marquet and Bechtold [2020], Marquet et al. [2022] and Marquet and Stevens [2022].

² In particular: Kelley [1932], Latimer et al. [1938], Rossini et al. [1952], Laidler [1956], Lewis and Randall [1961], Robinson and Stokes [1970], Robie et al. [1978], Wagman et al. [1982], Grenthe et al. [1992], Gokcen and Reddy [1996], Chase [1998], Atkins and de Paula [2014], Grenthe et al. [2020] and Atkins et al. [2023].

third law is used for the calorimetric calculations $S(T) = S(0) + \int_0^T c_p(T') d\ln(T') + \sum_k L_k(T_k)/T_k$ based on $S(T = 0 \text{ K}) = 0$, with the integral of the specific heat capacities $c_p(T)$ and including the impact of all phase changes at temperatures T_k with the latent heats $L_k(T_k)$. The third law also corresponds to the statistical calculations $S(T) = 0 + k \ln(W)$, where the 0 term indicates that no other arbitrary term must be added, where k is the Planck-Boltzmann constant and where W , the number of quantum configurations, must be evaluated at the absolute temperature T for all translational (Sackur-Tetrode-Planck), rotational and vibrational degrees of freedom of atoms and molecules. Note that if the original third law corresponds to both $S(T = 0 \text{ K}) = 0$ in the calorimetric formula and to the 0 term in the statistical one, this original definition of Planck [1911, 1917] must be nowadays amended by considering possible residual entropies $S(0) \neq 0$ at 0 K in the calorimetric formula only (but not the statistical one) and for a few species like H_2O (ice Ih), due to the next computations of Pauling [1935] and Nagle [1966].

Differently, almost all other definitions of the quantities called “entropies” in atmospheric and oceanic studies deviate from these methods, by choosing other reference values which differ from both the calorimetric and statistical-quantum values provided by the third law of thermodynamics. More precisely, the alternative definitions are obtained by arbitrarily cancelling out these reference entropy values at the zero Celsius temperature or the triple point at 0.01 C (instead of zero Kelvin) for dry air, liquid water and sea salts³. The fact that the values of the reference entropies have no impact in most oceanographic applications, unless one wants to calculate and study the entropy of seawater itself, is a key reason for the dominant approach where these reference entropies are defined arbitrarily as in TEOS10.

It is within this framework that the TEOS10⁴ software [McDougall et al., 2010] has been designed, with thermodynamic functions computed with greater consistency from the Gibbs function fitted on more numerous and more recent observed datasets than before. However, although Millero [2010, p.19] explained that “ (...) *new TEOS-10 (...) will be very useful to modelers examining the entropy and enthalpy of seawater,*” this TEOS10’s values can be amended to correspond to the third law of thermodynamics and Millero’s previous papers concerning the calculation of seawater entropy, due to arbitrary redefinitions made in TEOS10 of the reference entropies of liquid water and ocean salts. Moreover, there have been a few papers, other than those already cited, where the absolute definitions of entropies have been explicitly mentioned, or even taken into account: Lemmon et al. [2000] for the dry air; Feistel and Wagner [2005, 2006] for the liquid water.

Consequently, the aim of the present paper is to compute and study the absolute seawater entropy state variable on concrete cases (observed vertical profiles and surface analyzed datasets, as shown in the next Part II). The chosen methodology described in the Part I consists of reconciling the TEOS10 formulation, with all its advantages, with the use of absolute values of reference entropies, as prescribed by Millero and available in all thermodynamic tables.

The paper is organized as follows. I explain in the section 2 the way the standard seawater entropy is presently computed in the reference TEOS10 software (see the subsection 2.1). I then explained in the subsection 2.2 why there is a need to update the computations of this standard seawater entropy, by taking into account the absolute value for the (pure) liquid-water entropy recalled in the subsection 2.3, and also the absolute for the sea-salts entropies, first computed at 25°C in the subsection 2.4, and then at 0°C in the subsection 2.5, before to show in the subsection 2.6 how it is possible to modify the TEOS10 relationships to compute the seawater entropy for all conditions of temperature, salinity and pressure.

Several comparisons with observations and analysed surface datasets are conducted in the second part of the paper [Marquet, 2026]. In this first part are shown in the Section 3 two numerical applications. The impact of the salinity is studied in the subsection 3.1 with a comparison between the old Millero, the standard TEOS10 and the new absolute seawater entropy formulations. The classic $t - S_A$ oceanic

³ For instance in the contributions by Iribarne and Godson [1973, 1981], Emanuel [1994], Romps [2008], Pauluis et al. [2010], Raymond [2013] and Mrowiec et al. [2016], among so many others for the atmosphere, and in the contributions by Fofonoff [1962], Feistel [1993], Feistel and Hagen [1995], Wagner and Pruss [2002], Feistel [2003], Warren [2006], Feistel et al. [2008], Sun et al. [2008], McDougall et al. [2010], ..., up to McDougall et al. [2023] and Feistel [2024] for the ocean.

⁴TEOS10 in short for: “Thermodynamic Equation Of Seawater - 2010.” See: <http://www.teos-10.org/publications.htm>

diagrams is plotted in the Subsection 3.2 by adding the new absolute iso-entropy lines to the isopycnic (iso-density) lines. Furthermore, I describe in the subsection 3.3 other more general situations in physics where the absolute values of entropies impact different phenomena, with detailed computations shown in the Supplementary Materials [Marquet, 2025, hereafter referred to as “SM”], as well as answers to FAQs regarding the interest, or not, of studying the absolute entropies of the atmosphere and oceans.

I finally recall in the concluding Section 4 the main results of the paper.

2. Computations of seawater entropy

2.1. The standard TEOS10 present version

The aim of this section is to recall how the seawater entropy is calculated in the current standard version of TEOS10, and to show where the reference entropy values for liquid water and sea salts appear.

The specific entropy⁵ η called “entropy of seawater” is computed in McDougall et al. [2010, Eq. 2.10.1, p.20]⁶ as a derivative of the specific seawater Gibbs’ function g :

$$\eta(S_A, t, p) = - \left. \frac{\partial g}{\partial t} \right|_{S_A, p} = - \frac{1}{40} \left. \frac{\partial g}{\partial y} \right|_{S_A, p}, \quad (1)$$

where S_A is the absolute salinity, $t = T - 273.15$ the Celcius temperature (with T the absolute temperature), $p = P - P_{SO}$ the “sea pressure” (Eq. A.2.1, p.73) equal to the absolute pressure (P) minus the standard ocean surface sea pressure $P_{SO} = 0.101325$ MPa (given in the table D.4, p.145, and thus with p close to the depth, in meter, when expressed in dbar), and $y = t/(40^\circ\text{C})$ a dimensionless temperature variable (where $t_u = 40^\circ\text{C}$ is given in the table D.4, p.145).

The specific free enthalpy $g = G/m$ (with $m = 1$ kg) of a multi-component dilute aqueous electrolyte solution was previously derived according to Feistel and Hagen [1995, Eq. 4.9, p.266] from the practical osmotic factor considered in Lewis and Randall [1961, Eq. 23-4, p.334] and Falkenhagen and Ebeling [1971, Eq. 116, p.40], leading to a formulation that can be rewritten as

$$\begin{aligned} g = & (1 - C) \times \mu_w^0(T, P) + C \times \mu_s^0(T, P) \\ & + \sum_a \frac{X_a}{M_s} R T C \ln \left[X_a \frac{C}{1 - C} \frac{M_w}{M_s} \right] \\ & - \frac{[\sum_a N_a Z_a^2 e^2 / D(T, P)]^{3/2}}{\sqrt{36 \pi \nu(T, P) k T N_w}}, \end{aligned} \quad (2)$$

where: $C = 1.00488 S$ is the sea-salts concentration (i.e. the absolute salinity $S_A/1000$); $M_w \approx 18.0152$ g mol⁻¹ and N_w the molar mass and number of molecules of liquid water; $\mu_w^0(T, P)$ the specific chemical function at infinite dilution for liquid water, $\mu_a^0(T, P)$, X_a , M_a and N_a the specific chemical function at infinite dilution, molar fraction, molar mass and number of molecules for each of the n sea salts ($a = 1, 2, \dots, n$); $M_s = \sum_a X_a M_a \approx 31.4058$ g mol⁻¹ the mean molar mass of sea salts with $\sum_a X_a = 1$, $\mu_s^0(T, P) = \sum_a X_a M_a \mu_a^0(T, P) / M_s$ the mean specific sea-salts chemical function (at infinite dilution); and with the other terms in the third line described in Feistel and Hagen [1995, p.264-266].

According to McDougall et al. [2010, Eq. 2.6.1, p.15] the TEOS10 Gibbs function (2) is split in two and written as the sum of the ‘pure water’ (W) and ‘salinity’ (S) parts

$$g(x, y, z) = g_{\text{Fei03}}^W(y, z) + g_{\text{Fei08}}^S(x, y, z), \quad (3)$$

⁵It is of common use in oceanography to write the entropy with the symbols η or σ (instead of the symbol S generally used in thermodynamic since Clausius, Boltzmann and Planck), in order to keep the letters S , S_P or S_A for the salinity. Note that other symbols like ϕ are also used to denote the entropy, with for instance the T - ϕ atmospheric diagram still called “Tephigram” in the UK and Canada.

⁶I will refer in the present paper to the pages and numbers of Figures, Equations and Tables of the version of the TEOS10’s Manual downloaded in September 2024 from: http://www.teos-10.org/pubs/TEOS-10_Manual.pdf

with from (1) the entropy function written as

$$\eta(x, y, z) = \eta_{\text{Fei03}}^{\text{W}}(y, z) + \eta_{\text{Fei08}}^{\text{S}}(x, y, z), \quad (4)$$

both in terms of y and the other dimensionless salinity and pressure variables: $x^2 = S_{\text{P}}/40 = S_{\text{A}}/(40.188617 \text{ g kg}^{-1})$, where S_{P} is the practical salinity, and $z = p/(100 \text{ MPa})$ (see the table D.4, p.145, and the Appendices G and H, p.155-156).

The two Gibbs functions $g_{\text{Fei03}}^{\text{W}}(y, z)$ and $g_{\text{Fei08}}^{\text{S}}(x, y, z)$ were previously computed by Feistel [2003, Table 10-27, p.93] and Feistel [2008, Table 17, p.1666], respectively, as series expansions of $x^i y^j z^k$:

$$g_{\text{Fei03}}^{\text{W}}(y, z) = \sum_{j=0}^7 \sum_{k=0}^6 g_{0jk} y^j z^k \quad (5)$$

and

$$\begin{aligned} g_{\text{Fei08}}^{\text{S}}(x, y, z) = & \sum_{j=0}^6 \sum_{k=0}^5 [g_{1jk} x^2 \ln(x) \\ & + \sum_{i=2}^6 g_{ijk} x^i] y^j z^k, \end{aligned} \quad (6)$$

with the TEOS10 coefficients g_{ijk} listed in McDougall et al. [2010, Appendices G and H, p.155-156].

According to (1) applied to (3), and thus to (5) and (6), the entropy coefficients corresponding to (4) are $\eta_{ijk} = -(j+1) g_{i,j+1,k}/40$ and correspond to the relationships shown in the Tables 1 and 2, which enable to compute directly the TEOS10 seawater entropy without using the TEOS10 software⁷.

The way in which the two parts of g are defined in (3) can be understood by rewriting the first line of (2) using the definition $\mu_{\text{w}}^0 = h_{\text{w}} - T \eta_{\text{w}}$ and $\mu_{\text{s}}^0 = h_{\text{s}} - T \eta_{\text{s}}$ for the pure-liquid water and sea-salts chemical potentials, with the concentration $C = S_{\text{A}}/1000$ in kg kg^{-1} depending on the absolute salinity S_{A} in g kg^{-1} . Therefore, the first-order constant terms η_{w0} and η_{s0} (independent of T and P) of the entropy η impact the Gibbs function via the terms $(1 - S_{\text{A}}/1000) \eta_{\text{w0}} + (S_{\text{A}}/1000) \eta_{\text{s0}}$, which can be rewritten as $[\eta_{\text{w0}}] + [(\eta_{\text{s0}} - \eta_{\text{w0}})(S_{\text{A}}/1000)]$. This explains the natural splitting of this sum in the two TEOS10's Tables 1 and 2 (for $\eta_{\text{Fei03}}^{\text{W}}$ and $\eta_{\text{Fei08}}^{\text{S}}$) into the two bracketed 'pure-water' $[\eta_{\text{w0}}]$ and 'salinity' $[(\eta_{\text{s0}} - \eta_{\text{w0}})(S_{\text{A}}/1000)]$ parts, respectively. Other linear and non-linear variables terms generated by the three lines of (2) are similarly cast into the 'pure-water' and 'salinity' parts of g , and thus of η . In particular, the second line of (2) explains the term $x^2 \ln(x)$ with $x^2 = S_{\text{A}}/40.188617 = 24.88267 C$.

Therefore, the reference values of the entropies do not impact the pure-water part of the seawater entropy, since $[\eta_{\text{w0}}]$ is a mere constant with no physical meaning (null differential). Differently, the linear first-order salinity term must have a physical impact on the computation of the seawater entropy, since its differential $(\eta_{\text{s0}} - \eta_{\text{w0}})(dS_{\text{A}}/1000)$ is a priori different from zero and depends on the difference of the two reference values, and thus depends on both η_{s0} and η_{w0} , which must be determined in order to compute the absolute value of the seawater entropy η in (4) from the Tables 1 and 2.

The first choice retained in pre-TEOS10 formulations was to arbitrarily set $\eta_{\text{w0}} = 0$, in order to cancel the pure-water entropy at the triple-point conditions: $\eta_{\text{Fei03}}^{\text{W}}(T_{\text{t}}, p_{\text{t}}) = 0$ [McDougall et al., 2010, Eq. G.2, p.155]. In fact, in the present version of TEOS10 software the term η_{w0} is set to $-g_{010}/40 \approx -5.9056/40 \approx 0.14764$ instead, and $(\eta_{\text{s0}} - \eta_{\text{w0}})$ is set to $-g_{210}/40 \approx -168.0724/40 \approx 4.2018$, in order to arrive at the cancellation of the whole seawater entropy $\eta(S_{\text{SO}}, t_{\text{SO}}, p_{\text{SO}})$ for the arbitrary standard conditions $S_{\text{SO}} = 35.16504 \text{ g kg}^{-1}$, $t_{\text{SO}} = 0^\circ\text{C}$ and $p_{\text{SO}} = 0 \text{ dbar}$ [see the explanations p.155 and Eq. 2.6.6, p.17 of McDougall et al., 2010].

⁷ Namely as done in the part of the subroutine `gsw_gibbs.f90` of the software `GSW-Fortran-3.05-6` with the derivation options `"(ns.eq.0).and.(nt.eq.1).and.(np.eq.0)"`.

Table 1. The “pure-liquid-water” part of the sea-water entropy function computed from the TEOS10 software (see the g_{ijk} coefficients in the Appendix G, p.155), where $y = t/(40^\circ\text{C})$ and $z = p/(100\text{ MPa})$ are two dimensionless variables.

$$\begin{aligned}
 \underbrace{\eta_{\text{Fei03}}^{\text{W}}(y, z)}_{\text{“pure-Water”}} &= \underbrace{\{\eta_{\text{w0}}\}}_{\text{“???”}} + \left(\frac{1}{40}\right) \overbrace{\left(-5.90578347909402\right)}^{(-g_{010})} + \left(\frac{1}{40}\right) [270.983805184062 z \\
 &\quad - 776.153611613101 z^2 + 196.51255088122 z^3 - 28.9796526294175 z^4 \\
 &\quad + 2.13290083518327 z^5 + 24715.571866078 y - 2910.0729080936 y z \\
 &\quad + 1513.116771538718 y z^2 - 546.959324647056 y z^3 + 111.1208127634436 y z^4 \\
 &\quad - 8.68841343834394 y z^5 - 2210.2236124548363 y^2 + 2017.52334943521 y^2 z \\
 &\quad - 1498.081172457456 y^2 z^2 + 718.6359919632359 y^2 z^3 - 146.4037555781616 y^2 z^4 \\
 &\quad + 4.9892131862671505 y^2 z^5 + 592.743745734632 y^3 - 1591.873781627888 y^3 z \\
 &\quad + 1207.261522487504 y^3 z^2 - 608.785486935364 y^3 z^3 + 105.4993508931208 y^3 z^4 \\
 &\quad - 290.12956292128547 y^4 + 973.091553087975 y^4 z - 602.603274510125 y^4 z^2 \\
 &\quad + 276.361526170076 y^4 z^3 - 32.40953340386105 y^4 z^4 + 113.90630790850321 y^5 \\
 &\quad - 21.35571525415769 y^6 + 67.41756835751434 y^6 z - 381.06836198507096 y^5 z \\
 &\quad + 133.7383902842754 y^5 z^2 - 49.023632509086724 y^5 z^3].
 \end{aligned}$$

135 2.2. A need to update the seawater entropy

136 Since the seawater entropy can be written as $\eta(x, y, z) = \eta_{\text{w0}} + (\eta_{\text{s0}} - \eta_{\text{w0}}) (S_{\text{A}}/1000) + (\dots)$, where (...)
 137 represent the non-linear higher-order terms in x^2 , y or z , the first-order terms of the vertical gradient
 138 $\partial\eta/\partial z$ and the turbulent flux $\overline{w'\eta'}$ are the product of the measurable quantities $\partial S_{\text{A}}/\partial z$ and $\overline{w' S'_{\text{A}}}$ by
 139 the difference in reference entropy $(\eta_{\text{s0}} - \eta_{\text{w0}})$. Then, since the entropy is a thermodynamic state function,
 140 the difference of η between two points, and thus its gradients and turbulent fluxes, cannot be arbitrary
 141 and cannot be either positive, null or negative, depending on the values and signs of $\eta_{\text{s0}} - \eta_{\text{w0}}$. This
 142 means that it is not possible to modify or arbitrary set η_{s0} and/or η_{w0} to this or that values, unless to
 143 modify the entropy budget ($d\eta/dt = \dots$), and thus the second law of thermodynamics.

144 It may be decided not to bother with entropy calculations, since the reference entropy values have no
 145 impact on the other thermodynamic variables (specific volumes, heat capacities, expansion coefficients,
 146 sound speeds, osmotic pressure, etc), and only impact the entropy, Helmholtz free energy and Gibbs free
 147 enthalpy functions. But in this case, we have to go right to the end of the consequences, and refrain
 148 from calculating values of these three functions, leaving these three quantities undetermined to within a
 149 function of salinity.

150 Differently, one of the aims of TEOS10, as Millero reminded us, is to provide precise values for these
 151 three functions. So there is no choice if you want to calculate these three functions: you have to leave no
 152 room for arbitrariness and trust the recommendations of general thermodynamics. Here lies the strong
 153 motivation for using non-arbitrary values for not only the difference in reference entropies $\eta_{\text{s0}} - \eta_{\text{w0}}$,
 154 but in fact for both η_{s0} and η_{w0} , and thus to use the absolute, third-law values of them defined in
 155 thermodynamic.

156 In addition, although the formulations of Millero and Leung [1976] and Millero [1983] brought a clear
 157 theoretical improvement in taking into account the absolute reference entropies of liquid water and sea-
 158 salts, the analytical and numerical formulation seems somewhat anomalous (see the subsection 3.1). As

Table 2. The “saline” (sea-salts) part of the sea-water entropy function computed from the TEOS10 software (see the g_{ijk} coefficients in the Appendix H, p.156), with the dimensionless concentrations $C = X_A = S_A/1000$ and $X_{SO} = S_{SO}/1000$ and the dimensionless variables $x^2 = S_A/(40.188\,617\,g\,kg^{-1})$, $y = t/(40^\circ C)$ and $z = p/(100\,MPa)$, where S_A is the absolute salinity in units of $g\,kg^{-1}$ and $S_{SO} = 35.165\,04\,g\,kg^{-1}$ is a standard seawater salinity (see Table D.4, p.145).

$$\begin{aligned}
\overbrace{\eta_{\text{Fei08}}^S(x, y, z)}^{\text{“Salinity”}} &= \overbrace{\{\eta_{s0} - \eta_{w0}\}}^{\text{“???”}} \times \left(\frac{S_A - S_{SO}}{1000} \right) + \left(\frac{1}{40} \right) [\overbrace{(-168.072408311545)}^{(-g_{210})} x^2 \\
&\quad - 851.226734946706 \ln(x) x^2 - 729.116529735046 x^2 z + 343.956902961561 x^2 z^2 \\
&\quad - 124.687671116248 x^2 z^3 + 31.656964386073 x^2 z^4 - 7.04658803315449 x^2 z^5 \\
&\quad + 493.407510141682 x^3 - 543.835333000098 x^4 + 196.028306689776 x^5 \\
&\quad - 36.7571622995805 x^6 + 137.1145018408982 x^4 y - 148.10030845687618 x^4 y^2 \\
&\quad + 68.5590309679152 x^4 y^3 - 12.4848504784754 x^4 y^4 + 22.6683558512829 x^4 z \\
&\quad + 175.292041186547 x^3 z - 83.1923927801819 x^3 z^2 + 29.483064349429 x^3 z^3 \\
&\quad + 86.1329351956084 x^3 y - 766.116132004952 x^3 y z + 108.30162043765552 x^2 y^4 \\
&\quad - 51.2796974779828 x^3 y z^3 + 30.068211258562 x^3 y^2 + 1380.9597954037708 x^3 y^2 z \\
&\quad - 3.50240264723578 x^3 y^3 - 938.26075044542 x^3 y^3 z - 1760.062705994408 x^2 y \\
&\quad + 675.802947790203 x^2 y^2 - 365.7041791005036 x^2 y^3 + 108.3834525034224 x^3 y z^2 \\
&\quad - 12.78101825083098 x^2 y^5 + 1190.914967948748 x^2 y^3 z \\
&\quad - 298.904564555024 x^2 y^3 z^2 + 145.9491676006352 x^2 y^3 z^3 \\
&\quad - 2082.7344423998043 x^2 y^2 z + 614.668925894709 x^2 y^2 z^2 \\
&\quad - 340.685093521782 x^2 y^2 z^3 + 33.3848202979239 x^2 y^2 z^4 \\
&\quad + 1721.528607567954 x^2 y z - 674.819060538734 x^2 y z^2 + 356.629112415276 x^2 y z^3 \\
&\quad - 88.4080716616 x^2 y z^4 + 15.84003094423364 x^2 y z^5] .
\end{aligned}$$

159 a consequence, Millero’s calculations have to be restated using more recent data and methods.

160 2.3. The absolute entropy of pure liquid water

161 I recall in the second line of the Table 3 that the value of the absolute entropy of (pure) liquid water
162 is well-known since at least Lewis and Randall [1961, Table 12.3, p.137], who published the value
163 $16.73 \times 4.184 \approx 70.00\,J\,K^{-1}\,mol^{-1}$ at $25^\circ C$ retained in Millero and Leung [1976] and Millero [1983] and
164 corresponding, with the molar mass $M_w = 0.018\,015\,268\,kg^{-1}\,mol^{-1}$, to the value $3885.6\,J\,K^{-1}\,kg^{-1}$
165 at $25^\circ C$, and thus with $c_w \approx 4218\,J\,K^{-1}\,kg^{-1}$ to the value $3516\,J\,K^{-1}\,kg^{-1}$ at $0^\circ C$ ⁸.

166 This value represented by the purple disk in the Fig. 2(b), agrees with the value $3522 \pm 12\,J\,K^{-1}\,kg^{-1}$
167 from Giaque and Stout [1936] recalled by Feistel and Wagner [2005, p.104] in the improved IAPWS-
168 95 paper, and also agrees with the others values cited by Feistel and Wagner [2005, p.104]: $69.96 \pm$

⁸ The resulting correction term $4218 \times \ln(273.15/298.15) \approx -369.39\,J\,K^{-1}\,kg^{-1}$ is about -2 unit smaller than the value $-367.36\,J\,K^{-1}\,kg^{-1}$ computed with the TEOS10’s (GSW) subroutine (`liq_entropy_si`), with a smaller TEOS10’s mean value $\bar{c}_w \approx 4194.6\,J\,K^{-1}\,kg^{-1}$ between $298.15\,K$ and $273.15\,K$, and a larger Lewis-Randall and Millero and Leung pure-liquid water entropy of about $3518\,J\,K^{-1}\,kg^{-1}$ at $273.15\,K$.

Table 3. The molar mass (M , in g mol^{-1}), mole fraction (X , in mol mol^{-1}) and absolute entropies (S , in $\text{J K}^{-1} \text{mol}^{-1}$, ‘relative’ to $S(\text{H}^+) = 0$), computed at 25°C and 0.1 MPa , for the pure liquid water $(\text{H}_2\text{O})_{\text{liq.}}$ and the main sea-salts (cations and anions). Values of $M(\text{M82})$ are from Millero [1982, Table IV, p.428]; those of $X(\text{M83})$ are from Millero [1983, Table X, p.35], with about half the values of $X(\text{M83})$ normalized to a sum of 1; those of $M(\text{TEOS10})$ and $X(\text{TEOS10})$ are from McDougall et al. [2010, Table D.3, p.137], with the molar fractions obtained from the rounded values of Millero et al. [2008, Table 3, p.60]. The absolute entropies “M83” from Millero [1983, Table X, p.35] are the same as those in Millero and Leung [1976, Table 32, p.1071], and are in fact those previously listed in Lewis and Randall [1961, “LR61” in Table 25.7, p.400-401]. The more recent entropies “G92” are from Grenthe et al. [1992, “NEA-TDB” for “Nuclear Energy Agency and Thermodynamic Data Bank”, see the “Selected auxiliary data” p.64-83], which are still retained in Grenthe et al. [2020]. The numbers in parentheses refer to the uncertainty in the corresponding last digits, with for instance $96.0626(50)$ meaning 96.0626 ± 0.0050 .

	$M(\text{M82})$	$X(\text{M83})$	$S(\text{LR61/M83})$	$M(\text{TEOS10})$	$X(\text{TEOS10})$	$S(\text{G92})$
$(\text{H}_2\text{O})_{\text{liq.}}$			70.00	18.015 268		69.95(3)
(H^+)			(0.0)			(0.0)
Na^+	22.989 8	0.418 212 1	60.2	22.989 769 28(2)	0.418 807 1	58.45(15)
Mg^{2+}	24.305	0.047 558 3	−118	24.305 0(6)	0.047 167 8	−137(4)
Ca^{2+}	40.08	0.009 172 6	−55.2	40.078(4)	0.009 182 3	−56.2(10)
K^+	39.102	0.009 112 6	102.5	39.098 3(1)	0.009 115 9	101.2(2)
Sr^{2+}	87.62	0.000 080 0	−39.3	87.62(1)	0.000 081 0	−31.5(20)
Cl^-	35.453	0.487 541 5	55.2	35.453(2)	0.487 483 9	56.6(2)
SO_4^{2-}	96.057 6	0.025 217 1	17.2	96.062 6(50)	0.025 215 2	18.5(4)
HCO_3^-	61.017 2	0.001 725 5	95.0	61.016 84(96)	0.001 534 0	98.4(5)
Br^-	79.904	0.000 755 2	80.8	79.904(1)	0.000 752 0	82.55(20)
CO_3^{2-}	60.009 2	0.000 200 0	−51.3	60.008 9(10)	0.000 213 4	−50(1)
$\text{B}(\text{OH})_4^-$	78.839 6	0.000 075 0	(≈ 100)	78.840 4(70)	0.000 090 0	(102.5)
F^-	18.998 4	0.000 050 0	−9.6	18.998 403 2(5)	0.000 061 0	−13.8(8)
OH^-	(−)	(−)	−10.5	17.007 33(7)	0.000 007 1	−10.9(2)
$\text{B}(\text{OH})_3^{\text{aq.}}$	61.832 2	0.000 300 1	(≈ 50)	61.833 0(70)	0.000 280 7	162.4(6)
$\text{CO}_2^{\text{aq.}}$	(−)	(−)	(−)	44.009 5(9)	0.000 008 6	119.36(60)
Mean	31.405	1.000 000 0	47.52	31.404(1)	1.000 000 0	46.74(40)

0.03 $\text{J K}^{-1} \text{mol}^{-1}$ [from Cox et al., 1989] and $70.07 \pm 0.22 \text{ J K}^{-1} \text{mol}^{-1}$ (computed by Feistel and Wagner), including the residual entropy at 0 K of $3.407 \pm 0.001 \text{ J K}^{-1} \text{mol}^{-1}$ or $189.13 \pm 0.05 \text{ J K}^{-1} \text{kg}^{-1}$ [Pauling, 1935, Nagle, 1966], and is the same as the updated value $3516 \pm 2 \text{ J K}^{-1} \text{kg}^{-1}$ next considered by Feistel and Wagner [2006, p.1032].

I will retain for this study the smaller value

$$\eta_{\text{w0}} \approx 3513.4 \pm 1.7 \text{ J K}^{-1} \text{kg}^{-1} \text{ at } 0^\circ\text{C} \quad (7)$$

corresponding to $69.95 \pm 0.03 \text{ J K}^{-1} \text{mol}^{-1}$ at 25°C published in the NEA-TDB Tables by Grenthe et al. [1992, p.64] and Grenthe et al. [2020, p.149] recalled in the Table 3, also to $69.950 \pm 0.079 \text{ J K}^{-1} \text{mol}^{-1}$ published in the NIST-JANAF4 Tables by Chase [1998, p.1323], also to $69.9422 \text{ J K}^{-1} \text{mol}^{-1}$ in the Table B.6 by Schmidt [2022, p.889], and also to $69.91 \text{ J K}^{-1} \text{mol}^{-1}$ in the even more recent Tables by Atkins et al. [2023, p.893].

2.4. The absolute entropy of sea-salts at 25 °C

The mean absolute entropy for sea-salt aqueous ions have already been computed by Millero and Leung [1976, Table 32, p.1071] and Millero [1983, Table X, p.35], from the individual values $S(\text{LR61/M83})$ previously published by Lewis and Randall [1961, Table 25.7, p.400-401] and recalled in the Table 3. The resulting value was $95.01/1.99944 \approx 47.52 \text{ J K}^{-1} \text{ mol}^{-1}$ at 25°C in the papers by Millero, with a mean sea-salt molar mass $\langle A \rangle = 62.793/1.99944 \approx 31.405 \text{ g mol}^{-1}$ previously derived by Millero and Leung [1976, see M_2 in Eq. 10 in the Appendix, p.1074] leading to the sea-salt entropy $1513.1 \text{ J K}^{-1} \text{ kg}^{-1}$ at 25°C. The factor $1.99944 \approx 2$ was due to a definition of molal concentrations by Millero and Leung [1976] and Millero [1983] different from the molar concentration published by Millero et al. [2008, Tables 3 and 4, p.60 and p.62] and McDougall et al. [2010, Table D.3, p.137] and shown in the column $X(\text{TEOS10})$ in the Table 3.

Note that the sea-salt aqueous ions listed in the Table 3 are relative to $\bar{S}_{\text{H}^+}^\circ = 0$, with however no impact of a non-zero value for $\bar{S}_{\text{H}^+}^\circ$ on the mean value for the sea-salts entropy, because the mean value of the product of the valence (Z_j) and the mole fraction (X_j) is zero for the Millero's and TEOS10 setup [see the column for $X_j \times Z_j$ in the Table D.3 of McDougall et al., 2010, p.144].

However, Millero's articles suffer from the fact that they do not take into account the two species OH^- and CO_2^{aq} considered in the more recent studies and TEOS10. Accordingly, it would be interesting to use update and more recent values for the sea-salts entropies and concentrations, like the TEOS10's sea-salts values listed in McDougall et al. [2010, Table D.3, p.144], together with updated values from the molar absolute sea-salt entropies $\Delta_r S_m^\circ$ listed in the "Selected auxiliary data" in the NEA-TDB Tables IV.1 and IV.2 of Grenthe et al. [1992, S(G92), p.64-83] retained in Grenthe et al. [2020], including uncertainty intervals.

The corresponding updated mean values for $M(\text{TEOS10})$ and $S(\text{G92})$ shown in the Table 3 are:

$$M_s \approx 31.404 \pm 0.001 \text{ g mol}^{-1}, \quad (8)$$

$$\eta_{s0} \approx 46.74 \pm 0.40 \text{ J K}^{-1} \text{ mol}^{-1} \text{ (at 25°C)},$$

$$\eta_{s0} \approx 1488.3 \pm 13 \text{ J K}^{-1} \text{ kg}^{-1} \text{ (at 25°C)}, \quad (9)$$

which is only 24.8 units and 1.6 % smaller than the Millero's value. I have also computed (not shown) similar sea-salt entropies at 25°C from other datasets: 47.33 ± 2 from Latimer et al. [1934, Table III, p.84], 47.04 from Latimer et al. [1938, Table II, p.1831], 46.75 ± 0.4 from Robie et al. [1978, USG-1452] and 46.93 from Wagman et al. [1982, NBS-82].

2.5. The absolute entropy of sea-salts at 0 °C

In order to compute the mean reference sea-salt entropy at 0°C by using the relationship $S(273.15) = S(295.15) + \bar{C}_p^\circ \ln(273.15/298.15)$, it is needed to know the mean specific heats of sea salts at constant pressure \bar{C}_p° , for instance by averaging the individual values for each sea salts recalled in the Table 4 from several datasets, where individual values are not available for all species. For this reason, three kinds of averaging are made: first with the two main species 0.5% of Na^+ and 0.5% of Cl^- and the concentrations $X(2)$; then for the four main species Na^+ , Mg^{2+} , Cl^- and SO_4^{2-} (for LR61, HH96 and M12) and the concentrations $X(4)$; and then for the whole set of the eight species (for HH96 and M12 only) and the concentrations $X(8)$.

When available, the order of magnitude and the signs of \bar{C}_p° are similar for the 6 species Na^+ , K^+ , Cl^- , SO_4^{2-} , HCO_3^- and Br^- . The discrepancies is larger for Ca^{2+} and Mg^{2+} , with even not the same signs for Mg^{2+} . However, the value for Mg^{2+} computed in a recent paper Caro et al. [2020, Table 7, p.H] is negative (-155) and close to the value $-16 - 2 \times 71 = -158$ published in both HH96 and M12. For this reason the old positive values of LR61 for Mg^{2+} might be inaccurate.

Table 4. Values of the molar specific heat at constant pressure \overline{C}_p° at 25°C (in J K⁻¹ mol⁻¹) for several of the major sea-salt cations and anions, and based on $\overline{C}_p^\circ(\text{H}^+) = 0$: “LR61” from Lewis and Randall [1961, Table 25-7, p.400-401]; “NBS82” from Wagman et al. [1982, Tables p.2-47, 2-50, 2-57, 2-83, 2-260, 2-267, 2-299, 2-328]; “CM96” from Criss and Millero [1996, Table 2, p.1290]; “HH96” from Hepler and Hovey [1996, Table 5, p.647]. Conversions from the old unit (cal K⁻¹ mol⁻¹) of “LR61” are made with 1 cal = 4.184 J. The values “M12” from Marcus [2012, Table 1.2, p.12] was with $\overline{C}_p^\circ(\text{H}^+) = -71$ J K⁻¹ mol⁻¹ and have been transformed for the reference $\overline{C}_p^\circ(\text{H}^+) = 0$ by taking into account the valences of ions Z (-2, -1, +1, +2). The molar concentrations X (in mol mol⁻¹) are adapted from McDougall et al. [2010, Table D.3, p.137] recalled in the previous Table 3. The rescaled values lead to a sum of 1 for either the case $X(2)$ where only two major species (Na⁺ and Cl⁻) are available, or the case $X(4)$ where four major species (Na⁺, Mg²⁺, Cl⁻ and SO₄²⁻) are available, or the case $X(8)$ where all the eight species are available.

\overline{C}_p°	Na ⁺	Mg ²⁺	Ca ²⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	Br ⁻	Mean
$X(2)$	0.500				0.500				1.000
LR61	33.1	(+16.7)	(-37.7)	(9.6)	-126	(-276)	(...)	(-130)	-46.5
NBS82	46.4	(...)	(...)	(21.8)	-136.4	(-293)	(...)	(-141.8)	-45.0
CM96	43.01	(...)	(...)	(12.47)	-126.32	(...)	(-53.33)	(-131.27)	-41.7
HH96	42	(-16)	(-27)	(12)	-126	(-276)	(-52)	(-132)	-42.0
M12	43	(-16)	(-27)	(13)	-127	(-280)	(-53)	(-131)	-42.0
$X(4)$	0.427 93	0.048 20			0.498 10	0.025 77			1.000
LR61	33.1	+16.7	(-37.7)	(9.6)	-126	-276	(...)	(-130)	-54.9
HH96	42	-16	(-27)	(12)	-126	-276	(-52)	(-132)	-52.7
M12	43	-16	(-27)	(13)	-127	-280	(-53)	(-131)	-52.8
$X(8)$	0.419 12	0.047 20	0.009 19	0.009 13	0.487 84	0.025 24	0.001 53	0.000 75	1.000
HH96	42	-16	-27	12	-126	-276	-52	-132	-51.9
M12	43	-16	-27	13	-127	-280	-53	-131	-52.1

218 The mean value computed with 0.5% of Na⁺ and 0.5% of Cl⁻ are close to -42 to -46 units. The mean
219 values computed with the 4 major species Na⁺, Mg²⁺, Cl⁻ and SO₄²⁻ are more negative (by about 10
220 units) and remain close to each others (about -53 ± 2 units), which is close to the mean values computed
221 with the more complete set of 8 species (about -52 ± 1 units).

Therefore, the mean specific heat at constant pressure for sea salts may be set to:

$$\overline{C}_{ps} \approx -52 \pm 1 \text{ J K}^{-1} \text{ mol}^{-1}; \quad (10)$$

or with M_s given in (8):

$$\overline{C}_{ps} \approx -1656 \pm 30 \text{ J K}^{-1} \text{ kg}^{-1}. \quad (11)$$

The specific entropy of sea salts at 0°C can then be computed from the value of η_{s0} at 25°C given by (9), leading to:

$$\begin{aligned} \eta_{s0} &\approx (1488.3 \pm 13) - (1656 \pm 30) \times \ln\left(\frac{273.15}{298.15}\right), \\ \eta_{s0} &\approx 1633.3 \pm 15 \text{ J K}^{-1} \text{ kg}^{-1} \text{ (at 0°C)}. \end{aligned} \quad (12)$$

2.6. The TEOS10 absolute seawater entropy

It is thus possible to compute the absolute seawater entropy by considering the absolute values for the reference entropies η_{s0} and η_{w0} , to be taken into account in the standard TEOS10 value $\eta(x, y, z) = \eta_{\text{Fei03}}^{\text{W}}(y, z) + \eta_{\text{Fei08}}^{\text{S}}(x, y, z)$ recalled in (4) with the pure-water and salinity parts $\eta_{\text{Fei03}}^{\text{W}}(y, z)$ and $\eta_{\text{Fei08}}^{\text{S}}(x, y, z)$ shown in the Tables 1 and 2, respectively.

Both values of the constant terms η_{w0} and $-g_{010}/40 \approx 0.14764$ in $\eta_{\text{Fei03}}^{\text{W}}(y, z)$ have no physical impact (zero differential, and thus zero time derivatives, gradients and turbulent fluxes). Differently, the impact of the first-order salinity term in $\eta_{\text{Fei08}}^{\text{S}}(x, y, z)$, recalled in the first line of the Table 2, can be summarised by the increment term

$$\Delta\eta_s = (\eta_{s0} - \eta_{w0}) \times \frac{(S_A - S_{\text{SO}})}{1000} \quad (13)$$

(in $\text{J K}^{-1} \text{kg}^{-1}$) and have physical impacts on time derivative, gradients and turbulent fluxes of the seawater entropy. This increment must be understood as a way to compute the absolute entropy from the standard TEOS10 value, according to:

$$\eta_{\text{abs}} = \eta_{\text{std/TEOS10}} + \Delta\eta_s. \quad (14)$$

The underlying assumption is to trust the standard TEOS10 formulation to provide the entropy variations around the standard conditions where $\eta_{\text{std/TEOS10}}$ arbitrarily cancels out, amending this standard formulation to add the absolute-entropy increment $\Delta\eta_s$ with respect to S_{SO} that also cancels out for these standard conditions.

The present values for η_{s0} and η_{w0} due to the arbitrary hypothesis $\eta(S_{\text{SO}}, t_{\text{SO}}, p_{\text{SO}}) = 0$ made in TEOS10 can be replaced by the third-law absolute values at 0°C given in (12) and (7):

$$\begin{aligned} \eta_{s0} - \eta_{w0} &\approx (1633.3 \pm 15) - (3513.4 \pm 1.7), \\ \text{and } \Delta\eta_s &\approx (-1880 \pm 17) \times \frac{(S_A - S_{\text{SO}})}{1000} \end{aligned} \quad (15)$$

expressed in $\text{J K}^{-1} \text{kg}^{-1}$, with an uncertainty in $\Delta\eta_s$ of only 1 %.

The absolute-entropy increments (15) is large in comparison with the present (arbitrary) entropy value recalled in the first line of $\eta_{\text{Fei08}}^{\text{S}}(x, y, z)$ shown in the Table 2, with $x^2 = S_A/40.188617$ and $g_{210} \approx 168.072408311545$ leading to $-g_{210} \times (x^2/40) \approx -104.6 \times (S_A/1000)$ which is about 6% of the value of $\Delta\eta_s$ given by (15), and only 6 times the uncertainty in $\Delta\eta_s$.

3. Numerical applications

3.1. Comparisons with the Millero's entropy

It is useful to compare the old formulation derived by Millero and Leung [1976, p.1072] and Millero [1983, p.36] –recalled in Sharqawy et al. [2010b, Table 9, p.373] and Qasem et al. [2023, p.123]– with the linear relationships (13) and (15) for the increment term $\Delta\eta_s$ varying linearly with the TEOS10 absolute salinity variable $x^2 = S_P/40$, and thus depending on the absolute entropy reference values factor $(40/1000)(\eta_{s0} - \eta_{w0}) \approx -75.2 \pm 0.7 \text{ J K}^{-1} \text{kg}^{-1}$, leading to $\Delta\eta_s \approx -75.2 x^2$.

The Millero's relationships can be rewritten as

$$\eta_{\text{abs}} = \eta_w(y) + \eta_s(y, x), \quad (16)$$

$$\eta_s(y, x) = A(y) x^2 + B(y) x^3 + C(y) x^4, \quad (17)$$

where $\eta_w(y)$ and $\eta_s(y, x)$ was the pure-water and salinity parts of the seawater entropy, respectively, with $y = t/40$ the other TEOS10 temperature variable. The Millero's tuning values can then be rewritten (including a global factor 1000) as

$$A(y) = +56.872 - 0.4982 y + 0.27165 y^2, \quad (18)$$

$$B(y) = -55.054 + 4.1920 y - 0.65917 y^2, \quad (19)$$

$$C(y) = +16.322 + 1.0178 y - 0.60224 y^2, \quad (20)$$

for the salinity part expressed in unit of $\text{J K}^{-1} \text{kg}^{-1}$. The factor 1000 is due to the unit of $\text{J K}^{-1} \text{g}^{-1}$ (thus 1000 times larger) for the seawater entropy considered by Millero and Leung [1976, p.1072] and still retained by Sharqawy et al. [2010b, 373] and Qasem et al. [2023, p.123]. Note, however, that the unit was $\text{J K}^{-1} \text{mol}^{-1}$ (p.36) in Millero [1983], but $\text{J K}^{-1} \text{g}^{-1}$ in the Table II (p.11), which adds to the confusion...

The expected validity mentioned by Millero for the tuning of the salinity part (17)-(20) of the seawater entropy was: $0 \leq t \leq 40 \text{ }^\circ\text{C}$ and $0 \leq S_P \leq 40 \text{ kg}^{-1}$; and thus $0 \leq y \leq 1$ and $0 < x^2 < 1$ in terms of the TEOS10 variables.

The Millero's factors $A(y)$, $B(y)$ and $C(y)$ given by (18)-(20) can be compared with the corresponding leading order factors depending on x^2 , $x^2 y$, $x^2 y^2$, x^3 , $x^3 y$, $x^3 y^2$, x^4 , $x^4 y$ and $x^4 y^2$ listed in the Table 2 for $\eta_{\text{Fei08}}^S(x, y, z)$ and for $z = 0$, leading to the TEOS10 factors:

$$A'(y) = -4.2018 - 44.002 y + 16.895 y^2, \quad (21)$$

$$B'(y) = +12.335 + 2.1533 y + 0.7517 y^2, \quad (22)$$

$$C'(y) = -13.596 + 3.4279 y - 3.7025 y^2. \quad (23)$$

The additional TEOS10 non-linear term $[-21.281 \ln(x)] x^2$ is small and contribute to about $+1.42 x^2$ only for the standard salinity value $x^2 = 35/40$, and is moreover balanced by the TEOS opposite term $-4.2018 x^2$. Accordingly the Millero's leading-order term $+56.872 x^2$ is much larger than any other TEOS10 terms.

This large positive Millero's term has the opposite sign to the absolute entropy increment term $\Delta\eta_s \approx -75.2 x^2$ corresponding to (15) in the present paper, and to the salinity increment $\Delta\eta_s \approx -4.2 x^2$ in TEOS10, with negative impacts confirmed in the published Fig. 16 (p.374) of Sharqawy et al. [2010b]. This may be an explanation for the attempt to use in the MIT preprint version of Sharqawy et al. [2010a, Table 9, p.55] of the opposite sign for the whole Millero's salinity part, where $s_{\text{sw}} = s_w - \eta_s(y, x)$. However, the same Millero's positive impact $s_{\text{sw}} = s_w + \eta_s(y, x)$ is retained in the Fig. 5.1 (p.125) in Qasem et al. [2023], in contrast with the negative impact for all other formulas of Nayar et al. [2016], Chou [1968], Sun et al. [2008], Cooper and Dooley [2008, IAPWS] Pitzer [1987]

Another way of comparing these three formulations is to study the first entropy diagrams shown in the Figs. 1, where the salinity parts of the seawater entropies (similar to η_{Fei08}^S shown in the Table 2) are plotted against the absolute salinity and for three selected temperatures (0, 20 and 40 $^\circ\text{C}$). The positive increasing values for the Millero's formulation (blue lines) disagree with the decreasing values of the TEOS10 standard entropy (black lines). The red lines corresponding to the TEOS10 absolute entropy values are even more decreasing with both t and S_A . As entropy is a thermodynamic state function, its variations with salinity must have well-defined, non-ambiguous values, and the red curves and the absolute version of the reference entropies must be preferred to any others.

The Millero's formula is atypical compared to all the others, as shown in the Fig. 16 of Sharqawy et al. [2010b, p.374] and Fig. 5.1 of Qasem et al. [2023, p.125]. It was therefore difficult to have confidence in the numerical adjustment published in Millero's paper, with a need to improve the theoretical absolute entropy computations and to use more recent adjustments to new datasets, as done in the present paper

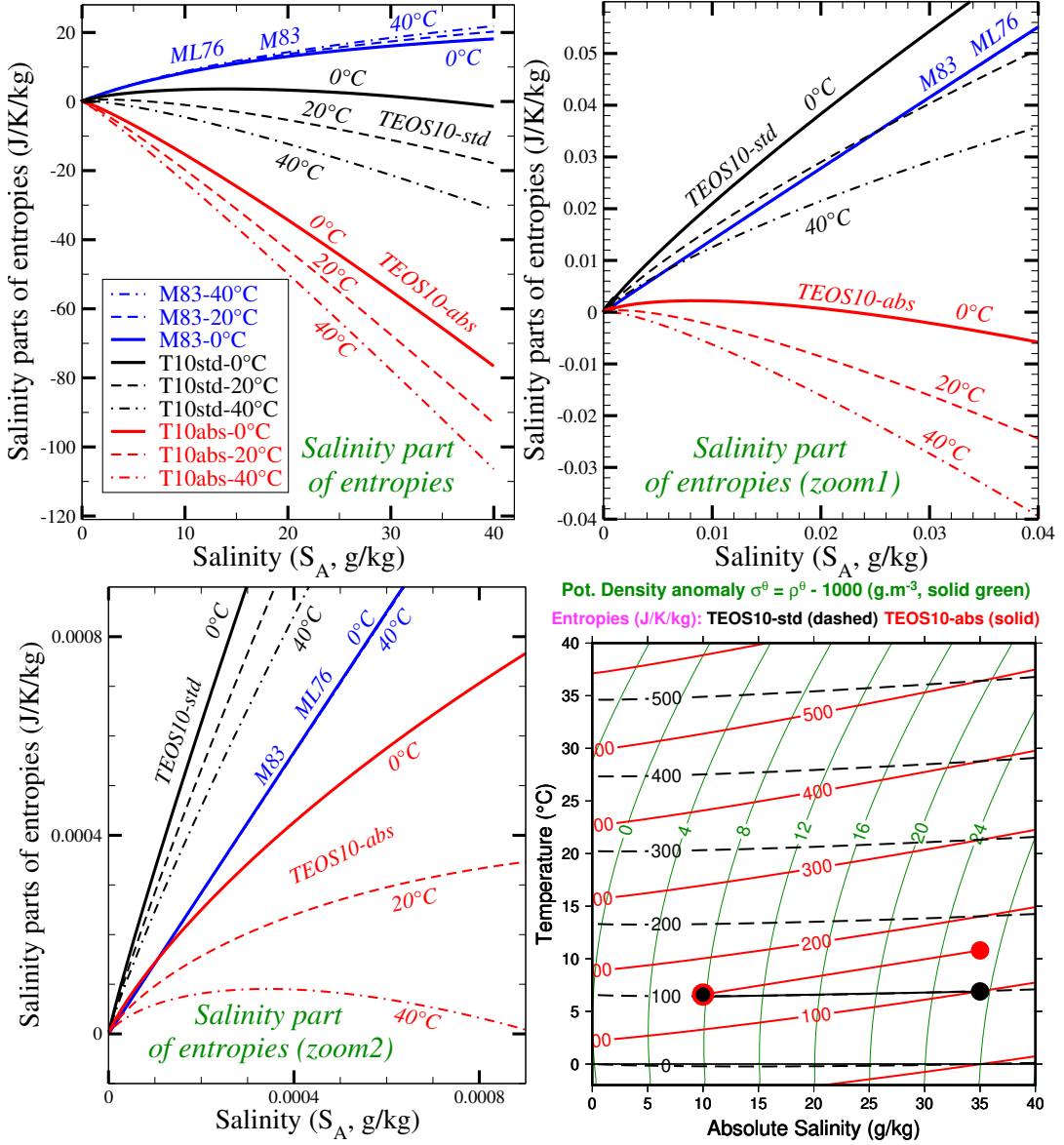


Figure 1. Top left: the salinity parts of the Millero's (1976-1983/blue) and TEOS10's (standard/black and absolute/red) seawater entropies plotted against the absolute salinity for three selected temperatures (0, 20 and 40 °C). Top right and Bottom left: two zoomed versions of this diagram for very small salinity, to show the impact of the term $x^2 \ln(x)$ corresponding to $S_A \ln(S_A)$. Bottom right: the isopycnic potential-density anomaly (solid green) lines, the standard TEOS10 entropy (dashed black) lines, and the new absolute TEOS10 entropy (solid red) lines are plotted on a classical $t-S_A$ Temperature-Salinity diagram. The three red and black circles represent isentropic processes (see the main text).

by starting with the more recent and accurate standard TEOS10 formulation, and then by adding to it the new updated absolute entropy increment $\Delta\eta_s$.

It should be noted that the decrease in entropy with salinity is not contrary to the fact that entropy must increase during the process of dissolving salts in pure water. As an example, the processes of dissolution of crystals of NaCl corresponds to a positive change in seawater entropy for the reaction $\text{NaCl}_{\text{cr}} \rightarrow (\text{Na}^+)_{\text{aq}} + (\text{Cl}^-)_{\text{aq}}$, with an entropy of $72.14 \text{ J K}^{-1} \text{ mol}^{-1}$ for a crystal of NaCl and a sum $59.00 + 56.36 = 115.36 \text{ J K}^{-1} \text{ mol}^{-1}$ for the separate ions $(\text{Na}^+)_{\text{aq}}$ and $(\text{Cl}^-)_{\text{aq}}$, leading to an increase of entropy of $115.36 - 72.14 = +43.22 \text{ J K}^{-1} \text{ mol}^{-1}$ representing the impact on the entropy of the dissolution of the NaCl crystal.

Differently, the decrease of the seawater entropy in the TEOS10's curves in the first entropy diagrams shown in the Figs. 1 should be interpreted as a decrease in the average entropy per unit mass when a mass of water with a higher salinity is added to another with a lower salinity, with the salts already dissolved in both masses of water and with a negative value in (15) for $\Delta\eta_s$ given by (13) due to $\eta_{s0} < \eta_{w0}$ for the absolute values of the reference entropies. In this sense, the errors in the tuning leading to the Millero's formulation (17)-(20) must have been corrected in the present formulation based on the amended version of TEOS10 using the absolute values of the reference entropies.

The impact of the term $x^2 \ln(x)$ in the TEOS10's entropy formulation, corresponding to the term $S_A \ln(S_A)$ introduced by Onsager and Fuoss [1932, Eq. 1.1.2, p.2689], is to create a vertical tangent at the origin. I show in the two zoomed diagrams plotted for very small salinity in the Figs. 1 that this behaviour starts to exist only for S_A much smaller than 1 g kg^{-1} , with in particular a general decrease of the absolute entropy for the whole oceanic range of salinity from 5 to 40 g kg^{-1} .

3.2. The temperature-salinity ($t - S_A$) diagram

The same results are obtained with the study of the other temperature-salinity ($t - S_A$) diagram plotted in the Figs. 1. The green lines are for constant values of the TEOS10 potential-density anomaly⁹ ($\sigma^\theta = \rho^\theta - 1000$, in g m^{-3}). Using potential density instead of local density will make it easier to compare the density of points of vertical profile at different depths in the second part of the paper, always using the same family of green lines (surface, $p_r = 0$).

In this $t - S_A$ diagram the new absolute seawater entropy (red lines) are different from the standard TEOS10 formulation (black lines): the new absolute values increase with the salinity, whereas the standard TEOS10 values are almost constant (especially for the smaller values of salinity and temperature). Similar differences (not shown) exist between the standard and absolute versions of the seawater entropy plotted with the entropy-temperature diagram published in Feistel et al. [2010, Fig.4, p.103].

Three black and red circles are plotted to show the differences in temperature associated with an isentropic process starting at about 6.6°C and with a change in salinity from 10 to 35 g kg^{-1} : the change in temperature is about 4°C greater for the absolute version than for the standard TEOS10 version ($\Delta t \approx +0.3^\circ\text{C}$ compared with $+4.2^\circ\text{C}$). This difference is significant, as shown by the applications to real cases described in the Part II.

It should be noted here (like in the Part-II) that the term “isentropic” (or same entropy) includes possible joint variations in pressure, temperature and salinity, without prejudging any adiabatic (no exchange of heat) or closed (same salinity) aspect of the evolution of ocean parcels. This is analogous to the definition of “isopycnal” processes, where density (or potential density) remains constant regardless of joint variations in pressure, temperature and salinity, with variations in temperature and salinity along isopycnals described with spiciness.

⁹Note that σ^θ is computed with the TEOS10's function `gsw_pot_rho_t_exact(sa,t,p,pr=0)` with the pressure changed to a fixed reference sea pressure anomaly $p_r = 0$ in an isentropic and isohaline manner [see McDougall et al., 2010, p.28].

3.3. General impacts of the Third law in physics

It may be important to recall the first validations for H_2 , Ar and Hg made close to 0 K and recalled by Nernst [1926, p.185-186] for the Sackur-Tetrode-Planck absolute entropy constants defined and studied by Planck [1917], Nernst [1918, 1921] and Planck [1921], where the theoretical and statistical-quantum absolute value $C_0 \approx -1.61$ was in agreement with the experimental and calorimetric third-law value $C_0 \approx -1.62 \pm 0.03$, in that allowing the computation of the saturation pressures from the third-law absolute entropies if the latent heats are known (see the section 12.1 in the SM).

It is possible to show another modern validation of the theoretical and calorimetric third-law absolute values computed at 0°C for the water-vapour and ice-Ih entropies. I have first computed (see the section 4.6 in the SM) the third-law statistical-quantum water-vapour entropy

$$\eta_{\text{v}/3\text{rd}}^{\text{stat.}}(T_0, p_0) \approx 10318 \pm 0.63 \text{ J K}^{-1} \text{ kg}^{-1}, \quad (24)$$

via the relationship $\eta = k \ln(W)$ represented by the blue arrow and the path up to the blue disk in the Fig. 2(b), with W corresponding to the translational, rotational and vibrational degrees of freedom of the 3D molecule H_2O . I have also computed, in a completely independent way (see the section 3.5 in the SM), the absolute calorimetric entropy for H_2O ice-Ih at 0°C

$$\eta_{\text{i}/3\text{rd}}^{\text{calor.}}(T_0) \approx 2295 \pm 13 \text{ J K}^{-1} \text{ kg}^{-1}, \quad (25)$$

via the relationship $\eta_0 + \int_0^T c_p(T') d\ln(T')$ represented by the red arrow and the path up to the red disk in the Fig. 2(b), with the experimental values of $c_p(T)$ plotted in the Fig. 2(a) and where $\eta_0 \approx 189 \text{ J K}^{-1} \text{ kg}^{-1}$ is the Pauling-Nagle residual entropy at 0°K . As a consequence, a new validation of the third law of thermodynamics can be obtained by computing the calorimetric water-vapour entropy at $T_0 = 273.15 \text{ K}$ and $p_0 = 10^5 \text{ Pa}$ via the relationship

$$\eta_{\text{v}/3\text{rd}}^{\text{calor.}}(T_0, p_0) = \eta_{\text{i}/3\text{rd}}^{\text{calor.}}[T_0, p_{\text{sat}}(T_0)] + \frac{L_{\text{sub}}(T_0)}{T_0} - R_{\text{v}} \ln \left[\frac{p_0}{p_{\text{sat}}(T_0)} \right] \approx 10320 \pm 13 \text{ J K}^{-1} \text{ kg}^{-1}, \quad (26)$$

where $L_{\text{sub}}(T_0) \approx 2834.5 \pm 0.5 \text{ kJ kg}^{-1}$ is the latent heat of sublimation, $R_{\text{v}} \approx 461.52 \text{ J K}^{-1} \text{ kg}^{-1}$ the gas constant for water vapour and $p_{\text{sat}}(T_0) \approx 611.15 \pm 0.10 \text{ Pa}$ the water-vapour saturation pressure over ice-Ih at 0°C . Clearly, this water-vapour absolute third-law calorimetric (26) and the previous statistical-quantum entropies (24) are in close agreement, up to 0.02 %.

Conversely, one can use (24) and (25) to calculate either the latent heat of sublimation $L_{\text{sub}}(T_0)$ or the saturation pressure $p_{\text{sat}}(T_0)$ variable from the other variable and from the difference in third-law entropies

$$\delta\eta(T_0, p_0) = \eta_{\text{v}/3\text{rd}}^{\text{stat.}}(T_0, p_0) - \eta_{\text{i}/3\text{rd}}^{\text{calor.}}[T_0, p_{\text{sat}}(T_0)] \approx 8023 \pm 13 \text{ J K}^{-1} \text{ kg}^{-1} \quad (27)$$

(i.e. the green arrow in the Fig. 2(b) in between the red and blue disks), by using the relationships

$$L_{\text{sub}}(\delta\eta, p_{\text{sat}}, T_0, p_0) = T_0 \left\{ \delta\eta(T_0, p_0) + R_{\text{v}} \ln \left[\frac{p_0}{p_{\text{sat}}(T_0)} \right] \right\} \quad (28)$$

$$\text{or } p_{\text{sat}}(\delta\eta, L_{\text{sub}}, T_0, p_0) = p_0 \exp \left[\frac{\delta\eta(T_0, p_0)}{R_{\text{v}}} - \frac{L_{\text{sub}}(T_0)}{R_{\text{v}} T_0} \right] \quad (29)$$

to arrive at $L_{\text{sub}}(T_0) \approx 2834.0 \pm 3.6 \text{ kJ kg}^{-1}$ or $p_{\text{sat}}(T_0) \approx 609 \pm 20 \text{ Pa}$, which are indeed in agreement with the experimental values. These calculations show the predictive power of the statistical (for water vapour) and calorimetric (for Ice-Ih) third-law independent computations leading to the blue and red disks, respectively, and these calculations form a validation of the physical significance of the third-law values of the entropy, by forming a little-known link between the numerical values of $L_{\text{sub}}(T_0)$ and

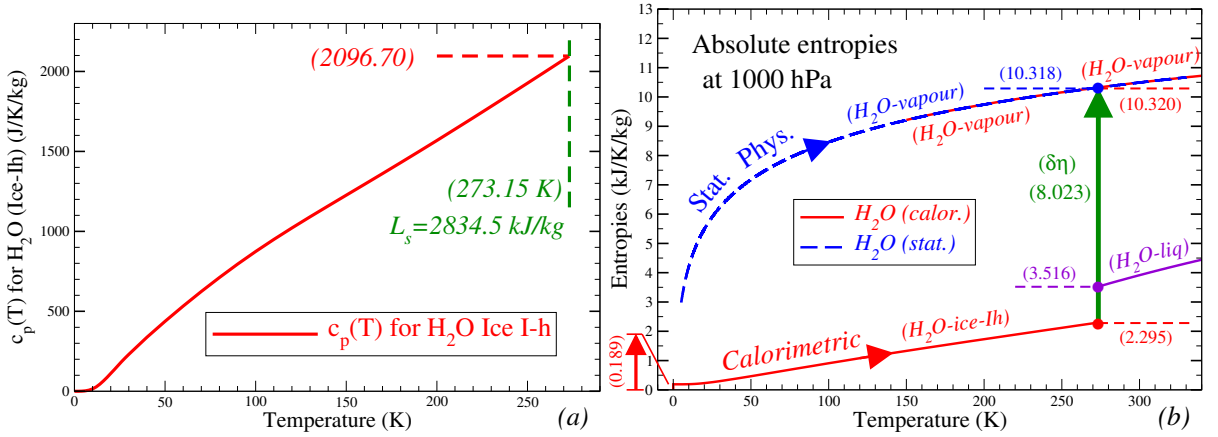


Figure 2. (a): The specific heat at constant pressure $c_p(T)$ for H_2O (Ice-Ih) for absolute temperatures T from 0 K to $T_0 = 273.15$ K. (b): The absolute entropies for H_2O (Ice-Ih, liquid and vapour) from 0 K to 340 K, with the calorimetric values $\eta_0 + \int_0^T c_p(T') d\ln(T')$ (solid red lines) including the Pauling-Nagle residual entropy $\eta_0 \approx 0.189$ kJ K⁻¹ kg⁻¹ at 0 K, and the statistical values $\eta = k \ln(W)$ (dashed blue line) automatically taking into account the residual entropy at 0 K and the latent heat of sublimation $L_{\text{sub}}(T_0) \approx 2834.5$ kJ kg⁻¹ at 273.15 K. The term $\delta\eta \approx 10.318 - 2.295 = 8.023$ kJ K⁻¹ kg⁻¹ (green arrow) is the difference between the statistical water-vapour and calorimetric Ice-Ih absolute entropies at $T_0 = 273.15$ K.

366 $p_{\text{sat}}(T_0)$, which are generally considered This creates an unexpected third-law implicit impact on the
 367 thermodynamic conditions at the surface of the oceans, and thus impacts the measurable evaporation
 368 processes.

369 Moreover I recall in the section 12.2 of the SM that the equilibrium constants of chemical reactions
 370 $K(T)$ ultimately depend on the absolute entropies S^0 of the reactants and products, via the well-known
 371 stability relationship $\Delta G_r = \Delta H_r - T \Delta S^0 = -R T \ln(K)$. General forms like $\ln(K) = \Delta S^0/R -$
 372 $\Delta H_r/(R T) = A + B/T + C \ln(T)$ are considered both in ozone chemistry [NASA-JPL publication by
 373 Burkholder et al., 2020] and seawater chemistry, where it was calculated in Weiss [1974] by adjustments to
 374 the observed data, considered for instance by Millero [1995] for the study of carbon dioxide concentration
 375 in the oceans, and more generally described in the DOE [Departement of Energy, 1994] publication. In the
 376 general form above the third-law absolute entropies of reactants and products must impact the constant
 377 term A . I show in the section 12.2 such an impact for the atmospheric reactions $\text{Cl} + \text{O}_2 \leftrightarrow \text{ClO}_2$ and
 378 $\text{NO} + \text{NO}_2 \leftrightarrow \text{N}_2\text{O}_3$ and the seawater reaction $\text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-}$ (ionization of the bicarbonate
 379 anion), where the constant terms A can be computed from the theoretical or experimental values of the
 380 third-law absolute entropies of molecules, anions and cations acting as reactants and products. Therefore,
 381 the concentrations of ozone in the atmosphere and of sea salts in the oceans both depend on the third-law
 382 absolute reference entropies as those considered in the present paper, in the Millero's papers and in some
 383 few others in atmospheric science [Hauf and Höller, 1987, Marquet, 2011, ...], via the photochemistry
 384 of the stratosphere and the electrolytic chemistry of the oceans. This is how the absolute values of
 385 the entropies influence the observed values of the concentrations of ozone and sea salts, and therefore
 386 with concentrations varying with the temperature and pressure which influence, in return and via the
 387 interactions with the radiations, on the vertical profiles of the temperature, which is an obvious observable
 388 quantity.

389 Moreover, I show in the section 12.9 of the SM that similar impacts exist for the turbulence acting

on the observable temperature-like variables, which, according to Richardson [1919, 1922], should be calculated via a turbulent mixing acting on the absolute entropy variable, and not on the temperature variable (see the section “*A need to update the seawater entropy*”). I show in the section 12.9 that the Lewis number (ratio of the thermal and water exchange coefficients) is different from unity for the moist-air absolute entropy variable θ_s , [Marquet, 2011], for which $K_s > 0$, and generates a counter-gradient term for the usually-used liquid-water potential temperature θ_l variable [Betts, 1973], for which K_h does not have even a definite sign. This means that the vertical and horizontal structures of temperature must ultimately depend on the absolute definition of the difference in entropy (like $s_{vt} - s_{dr}$ for the atmosphere and $\eta_{s0} - \eta_{w0}$ in the ocean) and the corresponding absolute-entropy exchange coefficients. Accordingly, it is possible to make a link between these atmospheric turbulent phenomena and those in the oceans, where currently several of the parameterizations are based on the principle of “*double diffusion*” first studied by Stern [1960] for the “*Salt-Fountain*” and still considered in Ma and Peltier [2024] for the polar oceans, where the exchange coefficients are different for the large-scale velocity (momentum), heat (temperature) and salinity, respectively [see for instance Canuto et al., 2002].

Moreover, in order to comply with Richardson’s requirements, an equivalent of the atmospheric variable $\theta_s = T_0 \exp[(s - s_{d0})/c_{pd}]$ [Marquet, 2011, Marquet and Stevens, 2022] to be used in turbulent schemes of oceanic simulations could be defined as the seawater absolute-entropy (potential?) temperature θ_η derived from the value of the absolute entropy η_{abs} given by (13), (14) and (15), but rewritten as $\eta_{abs} = c_w \ln(\theta_\eta/T_0)$, and thus with $\theta_\eta = T_0 \exp(\eta_{abs}/c_w)$ written as

$$\theta_\eta = 273.15 \times \exp\left(\frac{\eta_{std}/TEOS10}{4218}\right) \times \exp\left[(-0.446 \pm 0.004) \left(\frac{S_A - S_{SO}}{1000}\right)\right], \quad (30)$$

where $T_0 = 273.15$ K, $c_w \approx 4218$ J K⁻¹ kg⁻¹ and $S_{SO} = 35.16504$ g kg⁻¹. Note that the additive true constant term η_{w0} is discarded in the definition (30) that should be $\theta_\eta = T_0 \exp[(\eta_{abs} - \eta_{w0})/c_w]$ instead, simply because η_{w0} has already been discarded in the TEOS10 definition of the pure-water part η_{Fei03}^W recalled in the Table 1 (and only there in the present paper, as a true constant). This definition (30) for θ_η leads to exactly the same properties as the entropy η_{abs} because both c_w and T_0 are constant. However, θ_η (like θ_s for the atmosphere) is different from the associated entropy variable in that it has the same dimension (Kelvin) as the absolute temperature (T), the potential temperature (θ) and the conservative temperature (Θ) already provided as outputs of the TEOS10 software.

I show in the Figs. 42 to 44 in the section 12.9 of the SM that θ and Θ remain very close to each others for several arctic and tropical CTD profiles (up to $\pm 0.03^\circ\text{C}$). The differences between the actual temperature T and both θ and Θ are also small close to the surface (up to $\pm 0.03^\circ\text{C}$ for depths smaller than 250 dbar) where the impact of salinity on θ_η are the largest and can reach $\pm 1.5^\circ\text{C}$. Note the interesting feature that θ_η becomes similar to both θ and Θ for layers deeper than 3000 dbar (up to $\pm 0.04^\circ\text{C}$), where the differences with T can reach -0.6°C . These numerical evaluations confirm the potential of the θ_η variable to become a kind of thermal variable on which ocean turbulence is acting, and becoming a kind of “*absolute seawater potential temperature*” numerically similar to θ and Θ in deeper layers, but different from them in the mid and surface layers. This simply means that the seawater entropy (and thus θ_η) is very likely the more natural conservative variable.

All examples described in this section show that there is observable impacts in geophysics of the absolute reference entropy values, thereby providing a physical meaning for calculations and studies of absolute seawater entropy. However, the same doubts concerning the physical relevance of absolute entropy will continue to exist in atmospheric and oceanic sciences, much like doubts can still exist for the ultimate realism of the principles of many general principles of physics, such as the existence of the Michelson-Morley-Lorentz-Einstein’s limiting velocity (c) of physical phenomena in a vacuum, or the existence of the Planck’s quantum of action (h). There is no demonstration in the logical, mathematical or physical senses of these facts, which are simply observed, never disproved and therefore elevated to the

status of general principles. The same applies to the third law and the principle of unattainability of the absolute zero of temperature, subject to amending Planck [1911, 1917] formulation by adding possible residual entropies at 0 K in the calorimetric computations for some species like H_2O , as logically included in η_{abs} and θ_η for seawater.

Accordingly, other contributions than TEOS10 have admitted the possibility of at least considering as an option the absolute entropies for liquid water and dry air [Millero and Leung, 1976, Millero, 1983, Feistel and Hagen, 1995, Lemmon et al., 2000, Feistel and Wagner, 2006]. Nonetheless, it is often still considered that the TEOS10's choice is consistent with the first conclusion of the 5th International Conference on the Properties of Steam in London [5th-ICPS et al., 1956], which recommended (p.1/30-1/32 and 3/34) that the specific internal energy and the specific entropy of the liquid water should be set equal to zero at the triple point temperature of 0.01°C , instead of 0.00°C , without affecting any measurable thermodynamic properties of the climate system. However, I show in the section 12.5 and Fig. 32 of the SM that this first 1956 recommendation (p.3/34) was only valid for the case of a pure liquid-water steam system, and not for a mixture involving other species like in the moist-air atmosphere and the seawater. Moreover, it was decided at the same time [5th-ICPS et al., 1956, p.3/35-3/37] that the absolute values for the entropy of liquid water (computed from hypotheses made at 0 K) should also be mentioned in all subsequent studies. This is precisely what I have achieved in the present study by defining both η_{abs} and θ_η for seawater, including the impacts of absolute and non-arbitrary definitions for both pure liquid-water and sea-salt reference entropies.

4. Conclusion

In this paper the absolute seawater entropy η_{abs} , already derived theoretically in the papers by Millero published in 1976 and 1983, is computed and amended by adding the increment term $\Delta\eta_s$ given by (13) to the existing standard TEOS10's standard entropy formulations $\eta_{\text{std/TEOS10}} = \eta_{\text{Fei03}}^{\text{W}} + \eta_{\text{Fei08}}^{\text{S}}$ recalled in the Tables 1 and 2. The numerical value of this increment term proportional to both $\eta_{w0} - \eta_{s0}$ and S_A is given by (15).

The reference entropies at 25°C for pure liquid water (η_{w0}) and sea salts (η_{s0}) previously considered by Millero have been updated and computed at 0°C from more recent and complete thermodynamic datasets, to give the values (7) and (12) based on the third-law expressed by Planck [1911, 1917] who generalized the heat theorem of Nernst [1906]. Note that the residual entropy computed by Pauling [1935] and Nagle [1966] is automatically taken into account in the translational part of the entropy for liquid water, as it should and as recalled by Feistel and Wagner [2005, 2006].

Therefore, the present paper offers the possibility of amending, if needed, the current standard formulation of TEOS10 to calculate the seawater absolute entropy corresponding to the recommendations of the third law of thermodynamics.

As a result, the two entropy diagrams in Figs. 1 show large differences in magnitude (and even signs) for the changes in seawater entropy, as far as the salinity is not a constant. It should be worth adding the increment term $\Delta\eta_s$ wherever salinity values are particularly low or high, and wherever salinity gradients are large. I show in the second part of the paper several examples from observations and analysed datasets, where new isentropic features are revealed only with the absolute entropy of seawater, even though most of the oceanographic community believes that these differences have no physical significance.

Since the correction term $\Delta\eta_s$ depends on salinity, and thus varies not only spatially but temporally, the calculation of entropy itself is changed beyond the addition of a simple constant (like η_{w0} in $\eta_{\text{Fei03}}^{\text{W}}$ recalled in the Table 1). Consequently, because studies of the type “maximum entropy state” defined by $d\eta = 0$ depend on a certain combination of the differentials dT and $(\eta_{w0} - \eta_{s0}) dS_A$, there is an impact of the absolute reference entropy terms for non-stationary states with both $dT \neq 0$ and $dS_A \neq 0$, as for example for the regional, seasonal and climate changes.

Furthermore, insofar as the seawater entropy gradients regions influence the turbulent transport of this thermodynamic state variable, with turbulent flows which must cancel out in isentropic regions, the absolute definition of seawater entropy should impact the second principle of thermodynamics.

Increased accuracy could be achieved by re-adjusting the tuning of the TEOS10's formulation by using the absolute values of both η_{w0} and η_{s0} at 0°C, rather than using the value g_{010} and g_{210} as free adjustment variables in the Tables 1 and 2. Nonetheless, I think that adding the missing first-order correction term $\Delta\eta_s$, as did by Millero and the present paper as well, does not introduce major uncertainties, simply because most of non-linearities are already taken into account by using the well-founded standard TEOS10's version.

Since Fofonoff [1962, p.8], the prevailing view in the oceanographic community is that the choice of the linear salinity function $a_2 + a_4 S$ entering into the TEOS10 definition of the seawater entropy has no practical impact on known oceanographic applications, and that the choice of fixing a_2 and a_4 is a matter of convention. However, some people think that the Millero and TEOS10 approaches may be considered valid, and that neither should be subject to general rejection. It is within this last absolute-entropy framework that the present and Millero's papers are situated, inline with the previous books of Fowler [1929], Guggenheim [1933] and Guggenheim [1950] where the third law of thermodynamics and the Sackur-Tetrode translational entropy were fully considered, even if Guggenheim rather called the absolute value of entropy the "*conventional*" entropy.

Feistel [2019] has recently decided to take the debate to the related subject of the physical meaning of the residual entropy of ice at 0 K. This is a subject that is different from the translational, quantum degrees of freedom and the absolute (or not) status of entropy, and this subject of residual entropy only concerns a few species such as H₂O, N₂O and CO, for which proton disorder still exist at 0 K. In any case, it is clear that only by taking into account the residual entropy for H₂O computed by Pauling [1935] and Nagle [1966] can the calorimetric and quantum calculations of absolute entropy coincide, as shown in the Fig. B1 of Marquet and Stevens [2022] and as taken into account in all thermodynamic Tables [for instance in Lewis and Randall, 1961, Chase, 1998, Atkins and de Paula, 2014, Schmidt, 2022, Atkins et al., 2023].

For my part, I have complete confidence in these thermodynamic tables, rather than continuing to apply only the first pure-liquid water arbitrary recommendations expressed (p.3/34) in 1956, and not the following one (p.3/35-37) about the need to compute the absolute version of the entropy, and in particular for the more general case of a mixture of variable composition like the seawater as shown in this study. Moreover, the residual entropies are small quantities and should not overshadow the much more fundamental aspect of the absolute values of the entropies due to the impact of the translational degrees of freedom of atoms and molecules, as calculated by Sackur, Tetrode and Planck in the years 1911 to 1917. Indeed, if the residual entropy 189.13 J K⁻¹ kg⁻¹ was removed from η_{w0} given by (7), the result 3324.3 J K⁻¹ kg⁻¹ would be only 5.3 % smaller and the factor 1880 J K⁻¹ kg⁻¹ in $\Delta\eta_s$ given by (15) would be 1691 J K⁻¹ kg⁻¹ and only 10 % smaller, and thus with a small impact.

It is true that most observable thermodynamic quantities do not depend on reference values of pure-water and sea-salts entropy (specific volumes, heat capacities, expansion coefficients, sound speeds, osmotic pressure, etc). But these reference values impact at least the seawater entropy itself, which deserves to be calculated and studied as one of the major thermodynamic state functions, as confirmed by the interesting features revealed by the present study and the next part II.

Conflicts of interest

The author declares no competing financial interest.

Dedication

The author has given approval to the final version of the manuscript.

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The TEOS10-GSW Oceanographic FORTRAN software has been downloaded from <https://www.teos-10.org/software.htm> [McDougall and Barker, 2011].

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Supplementary data

Supplementary materials are provided in the Zenodo file Marquet [2025].

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