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Technical note: TEOS-10 EXCEL - Implementation of the Thermodynamic Equation Of Seawater - 2010 in EXCEL

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Abstract. This paper and associated software implement the Thermodynamic Equation Of Seawater - 2010 (TEOS-10) in EXCEL for an expedite estimation of *absolute salinity* (S_A), *conservative temperature* (Θ) and derived thermodynamic properties of seawater – *potential density* (σ_Θ), *in situ density* ($\rho_{S_A,\,\Theta,\,p}$) and *sound speed* (c). Vertical profile template plots for these parameters are included, as well as a S_A - Θ diagram template, which includes plotting of the density field (computation of user selected σ_Θ lines is included). Estimation of *absolute salinity* relies on the interpolation of data from casts of seawater from the world ocean (IOC, SCOR and IAPSO, 2010), and the EXCEL workbook introduced here (TEOS-10 EXCEL, available at https://doi.org/10.5281/zenodo.4763574) includes a subset of the TEOS-10 look-up tables necessary for this estimation, namely the *salinity anomaly* [deltaSA_ref] and the *absolute salinity anomaly ratio* [SAAR_ref] look-up tables. As the user simply needs to paste new data into the spreadsheet to automatically compute the oceanographic parameters referred above, this tool may prove to be extremely useful among all who are not comfortable of using the full-featured TEOS-10 programming language environments (e.g., MATLAB, FORTRAN), but rather need a simpler way of computing fundamental properties of seawater (e.g., density, sound speed), while adhering to current standards. Returned values are the same (up to 15 decimal places, i.e., difference = 0.000000000000000), as the ones obtained with the MATLAB version of the GSW (Gibbs Sea Water) toolbox (McDougall and Barker, 2011) available at the TEOS-10 website (https://www.teos-10.org). This paper describes the EXCEL workbook, its use, and the included VBA (Visual Basic for Applications) functions. Quality control against the GSW toolbox is also addressed, namely issues detected with the interpolated values returned by the toolbox when there are missing values in the reference look-up table. In these situations, the GSW toolbox replaces missing values with a level pressure horizontal interpolation of neighbour points, while it is clear from the testing results that vertical interpolation, which was then implemented in TEOS-10 EXCEL, returns a more robust solution (figs. 9 and 10).

1. Introduction

The development of software to facilitate the efficient analysis of the properties of seawater has allowed users to better understand the marine environment, assisting members of the student, research, and industrial communities alike. One such initiative, the Gibbs Sea Water (GSW) Toolbox (McDougall and Barker, 2011), implements the Thermodynamic Equation of

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Seawater – 2010 (TEOS-10) into software that rapidly calculates required seawater properties through utilisation of the MATLAB programming language. However, the software requires a working understanding and knowledge of MATLAB and of programming generally. As such, the toolbox may not be as readily accessible to all practitioners within the field of marine data analysis (e.g., Buzzetto-More et al., 2010; Bosse and Gerosa, 2017). The aim of this paper is to present an implementation of TEOS-10, within Microsoft EXCEL, a popular and readily available application. This new implementation requires no specialist knowledge to operate; it is therefore hoped that all groups interested in analysing sea water properties may benefit from free and open access to this new tool.

Seawater can be defined as a thermodynamic system with one liquid phase and two components: i) pure water and ii) dissolved salts. At the end of the XIX century, J. Willard Gibbs, established the *Gibbs phase rule* (Gibbs, 1874–1878) which states that, for a multiphase system in thermodynamic equilibrium, such as seawater, the degrees of freedom of the system, i.e., the number of independent variables needed to define it, equals the number of components subtracted by the number of phases plus two. For seawater this adds to three (2-1+2) and the 'chosen' variables are Salinity, Temperature and Pressure. The properties related to the three variables must be conservative, i.e., must not globally change within the system (i.e., the ocean), by opposition to non-conservative properties that are created and consumed within it (e.g., oxygen).

If the concept of pressure and temperature have remained pretty much unaltered over time (although the temperature standard changed in 1989 from IPTS-68 to ITS-90 (Preston-Thomas, 1990)), the definition of salinity has suffered significative variations during the last century (Millero, 2010). The current Thermodynamic Equation Of Seawater - 2010 (TEOS-10) has introduced a new salinity quantity, *absolute salinity* (S_A), that can be defined as "the mass fraction of dissolved material in seawater" (IOC, SCOR and IAPSO, 2010: 3). Accompanying S_A, a new temperature quantity, *conservative temperature* (Θ), was also introduced. *Conservative temperature* is estimated from *potential temperature* (θ) and S_A and is two orders of magnitude more conservative than θ (IOC, SCOR and IAPSO, 2010: 5). These two new quantities, S_A and Θ, together with *pressure* (p), are now the arguments of the equation of state, and to compute any thermodynamic property of seawater (e.g., density, sound speed) they must be estimated first. *Practical salinity* (S_P), which was used before in the Equation of State – 80 (EOS-80), is however still required for the determination of S_A and remains being the salinity quantity recommended to be archived in oceanographic data bases (IOC, SCOR and IAPSO, 2010: 8).

The polynomial nature of EOS-80 allowed the easy implementation of algorithms for computation of seawater properties, which led to the proliferation of stand-alone applications, interactive web sites and Visual Basic for Applications (VBA) modules. In TEOS-10 however, *absolute salinity* can be only estimated from interpolation of measured absolute salinity anomalies stored in a world atlas look-up table. This difficulty might be a possible explanation for the absence of any previous implementation of TEOS-10 in EXCEL. Section 2 introduces the new workbook, explains its operation, and describes the access to the world ocean look-up tables. Section 3 describes the translation of the original MATLAB code into VBA and

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discusses the interpolation method used for missing data in the reference look-up table, followed by the conclusion and summary in Section 4.

2. The TEOS-10 EXCEL Workbook

An EXCEL workbook file that implements a sub-set of the GSW (Gibbs Sea Water) toolbox (available at the TEOS-10 website https://www.teos-10.org) accompanies this paper. The file includes sample data that can be easily replaced by new user data to obtain ocean vertical profiles and $S_A - \Theta$ diagrams. The computation algorithms are implemented as VBA functions and are used as any other standard EXCEL function. The TEOS-10 world ocean look-up tables of measured *absolute salinity anomaly* [deltaSA_ref] and *absolute salinity anomaly ratio* [SAAR_ref], essential to estimate *absolute salinity*, are included in the workbook and are described later in the paper. The desktop App version of Microsoft Office is needed to use the workbook, as *VBA Macros do not run in Microsoft Web Office*. On opening the EXCEL file, authorisation for running macros must be granted.

The workbook (Fig. 1) contains four data spreadsheets (three green tabs and one yellow), two plotting spreadsheets (blue tabs) and six TEOS-10 look-up tables (purple tabs). Pressing [Alt – F11] opens the VBA environment allowing access to the 13 function modules, although access to these is not required to make use of the Workbook, nor is a working knowledge of VBA.

2.1 The green data tabs

The structure of the three green data tabs is identical, the only difference being the data sets incorporated in each. The 'TEOS-10 Test Data' spreadsheet includes a testing data set from the GSW Toolbox, located in the NW Pacific at 162.5º E 33º N. 'TS-55' data is a 1º longitude x 1º latitude historical average vertical profile in the NE Atlantic, off the Iberian Peninsula, centred at 10.5º W 40.5º N, with pressure levels interpolated to standard 'Levitus' levels (Levitus, 1982), and 'CTD-020' is a CTD cast in the same grid bin, at 10º 01' W 40º 05' N (Martins, 1998). Seawater properties in coloured columns are computed on the fly from user data input in white cells. The data included (in white cells) can be replaced by user data. Spreadsheet lines can be added (or deleted) and, if additional lines are required, it would only be needed to copy down the coloured cells for the formulae to propagate over the extra lines, without any further adjustments being necessary. The only caution users should have, is to *not move* the data (white cells) to other locations, as the spreadsheet formulae will 'follow' this operation, disrupting the original cell referencing. Users may also add new data spreadsheets to the EXCEL workbook, where they can then simply paste the whole content of one of the original data tabs for the new spreadsheet to become fully functional.

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	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Longitude	162.5	degrees	Replace **Pressure, Pratical Salinity** (or Conductivity) and **Temperature** data (either ITS-90 or IPTS-68), including **Longitude** and **Latitude**													
2	Latitude	33	degrees	All colour colums will update automatically. DATA CAN BE DELETED BUT **NOT MOVED prior to deletion** OR THE FORMULAS WILL LOOSE THEIR REFERENCE.													
3	Conductivity (C)	Pressure (p)	Practical Salinity (S_P)	Temperature (t) ITS-90	Temperature (t) IPTS-68	S_P from C	Reference Salinity (S_R)	delta S_A Atlas	SAAR Atlas	Salinity Anomaly (δS_A)	Absolute Salinity (S_A)	t ITS-90	Potential t (θ)	Conservative Temperature (Θ)	Potential Density (σ_Θ)	In situ Density ($\rho_{SA,\Theta,p}$)	Sound Speed (c)
4	(mS cm^{-1})	(dbar)		(ºC)	(ºC)		(g kg^{-1})	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})	(ºC)	(ºC)	(ºC)	(kg m^{-3} - 1000)	(kg m^{-3})	(m s^{-1})
5		0	34.57586	19.507610		34.5759	34.7389	0.000327101505	0.000009410247	0.000326901616	34.7392	19.5076	19.5076	19.5130	24.5709	1024.5709	1519.5537
6		10	34.74774	20.008300		34.7477	34.9116	0.000339231758	0.000009773386	0.000341204433	34.9119	20.0083	20.0065	20.0072	24.5716	1024.6148	1521.2985
7		20	34.67881	19.133780		34.6788	34.8423	0.000333521900	0.000009747636	0.000339630409	34.8427	19.1338	19.1302	19.1319	24.7466	1024.8333	1518.9494
8		30	34.68279	18.834320		34.6828	34.8463	0.000375042687	0.000010581871	0.000368739417	34.8467	18.8343	18.8290	18.8302	24.8264	1024.9566	1518.2704
9		40	34.68397	18.288160		34.6840	34.8475	0.000389800378	0.000011376763	0.000396451974	34.8479	18.2882	18.2813	18.2817	24.9648	1025.1387	1516.8712
10		50	34.68861	17.893830		34.6886	34.8522	0.000430311850	0.000012931657	0.000450696471	34.8526	17.8938	17.8853	17.8852	25.0661	1025.2838	1515.8962
11		76	34.69963	17.056150		34.6996	34.8633	0.000569195077	0.000016219010	0.000565447460	34.8638	17.0561	17.0436	17.0423	25.2778	1025.6097	1513.8627
12		101	34.69791	16.492310		34.6979	34.8615	0.000696512528	0.000019779266	0.000689535385	34.8622	16.4923	16.4761	16.4742	25.4100	1025.8520	1512.5741
13		126	34.71489	16.128460		34.7149	34.8786	0.000843341842	0.000023960698	0.000835715273	34.8794	16.1285	16.1085	16.1059	25.5080	1026.0600	1511.8947
14		151	34.68967	15.684310		34.6897	34.8532	0.001001694449	0.000028396145	0.000989697859	34.8542	15.6843	15.6608	15.6585	25.5905	1026.2530	1510.9066
15		176	34.65537	15.247770		34.6554	34.8188	0.001146533554	0.000032958859	0.001147587425	34.8199	15.2478	15.2209	15.2191	25.6623	1026.4358	1509.9149
16		202	34.63723	15.028760		34.6372	34.8006	0.001306176088	0.000038329968	0.001333904319	34.8019	15.0288	14.9982	14.9967	25.6975	1026.5858	1509.6304
17		252	34.58649	14.440070		34.5865	34.7496	0.001555687022	0.000045929491	0.001596030542	34.7512	14.4401	14.4029	14.4022	25.7872	1026.8977	1508.5164
18		303	34.53391	13.762160		34.5339	34.6968	0.001918317195	0.000056693585	0.001967083277	34.6987	13.7622	13.7189	13.7189	25.8905	1027.2291	1507.0947
19		353	34.44696	12.587460		34.4470	34.6094	0.002406799849	0.000074277399	0.002570695638	34.6120	12.5875	12.5399	12.5411	26.0606	1027.6275	1503.9112
20		404	34.37410	11.610510		34.3741	34.5362	0.003092026444	0.000101116678	0.003492184663	34.5397	11.6105	11.5588	11.5609	26.1915	1027.9920	1501.3222
21		505	34.17681	8.998112		34.1768	34.3380	0.004943227283	0.000152354201	0.005231533736	34.3432	8.9981	8.9428	8.9471	26.4886	1028.7658	1493.3821
22		606	34.04839	6.567234		34.0484	34.2089	0.007328918773	0.000217880674	0.007453467487	34.2164	6.5672	6.5115	6.5167	26.7417	1029.5063	1485.5902
23		707	34.05378	5.180429		34.0538	34.2144	0.010134516840	0.000293431730	0.010039578297	34.2244	5.1804	5.1224	5.1270	26.9196	1030.1657	1481.6929
24		808	34.13533	4.453866		34.1353	34.2963	0.012801564089	0.000365710401	0.012542510966	34.3088	4.4539	4.3914	4.3949	27.0677	1030.7880	1480.4628
25		909	34.21526	4.010992		34.2153	34.3766	0.014899810655	0.000425738110	0.014635428541	34.3912	4.0110	3.9430	3.9457	27.1798	1031.3704	1480.3736
26		1010	34.28701	3.630195		34.2870	34.4487	0.016512321555	0.000473242399	0.016302579738	34.4650	3.6302	3.5568	3.5588	27.2768	1031.9375	1480.5196
27		1111	34.33858	3.351287		34.3386	34.5005	0.017685037469	0.000508934903	0.017558509209	34.5181	3.3513	3.2720	3.2736	27.3463	1032.4752	1481.0620
28		1213	34.38449	3.102174		34.3845	34.5466	0.018687486637	0.000538076023	0.018588711984	34.5652	3.1022	3.0169	3.0181	27.4074	1033.0086	1481.7362
29		1314	34.42426	2.876307		34.4243	34.5866	0.019494191089	0.000561454629	0.019418798328	34.6060	2.8763	2.7851	2.7861	27.4607	1033.5292	1482.4828
30		1416	34.45672	2.694073		34.4567	34.6192	0.020176311159	0.000582091514	0.020151541483	34.6393	2.6941	2.5966	2.5974	27.5037	1034.0426	1483.4231
31		1517	34.48842	2.506860		34.4884	34.6510	0.020753899596	0.000599223978	0.020763738622	34.6718	2.5069	2.4034	2.4040	27.5459	1034.5510	1484.3241
32		1771	34.54501	2.196994		34.5450	34.7079	0.021602210963	0.000617441618	0.021430104714	34.7293	2.1970	2.0767	2.0772	27.6186	1035.7882	1487.2625
33		2025	34.58881	1.953304		34.5888	34.7519	0.021906208811	0.000625378399	0.021733094502	34.7736	1.9533	1.8154	1.8157	27.6744	1037.0030	1490.4856
34		2279	34.61341	1.825799		34.6134	34.7766	0.021834954336	0.000625665801	0.021758546231	34.7984	1.8258	1.6682	1.6684	27.7053	1038.1828	1494.2095
35		2534	34.63526	1.709283		34.6353	34.7986	0.021631273849	0.000621030221	0.021610969888	34.8202	1.7093	1.5312	1.5314	27.7329	1039.3583	1498.0128
36		2789	34.64812	1.626311		34.6481	34.8115	0.021385378943	0.000614436829	0.021389468131	34.8329	1.6263	1.4264	1.4267	27.7507	1040.5169	1501.9703
37		3045	34.65890	1.566066		34.6589	34.8223	0.021139155635	0.000607589802	0.021157693528	34.8435	1.5661	1.3432	1.3434	27.7651	1041.6695	1506.0602
38		3300	34.66710	1.527974		34.6671	34.8306	0.020918230176	0.000601218243	0.020940774256	34.8515	1.5280	1.2809	1.2811	27.7759	1042.8067	1510.2450
39		3556	34.67315	1.503932		34.6732	34.8366	0.020701479725	0.000595069372	0.020730222690	34.8574	1.5039	1.2314	1.2317	27.7841	1043.9387	1514.5230
40		3812	34.67689	1.489079		34.6769	34.8404	0.020516621253	0.000589541645	0.020539870502	34.8609	1.4891	1.1901	1.1903	27.7898	1045.0614	1518.8548

TEOS-10 Test Data | TS-55 | CTD-020 | Surface Data | Vertical Profiles | SA - Θ Diagram | longs_ref | lats_ref | ndepth_ref | p_ref | deltaSA_ref | SAAR_ref

Figure 1: TEOS-10 EXCEL workbook green data tab. Seawater properties in coloured columns are computed on the fly from user data pasted into white cells.

2.1.1 Data input

- Location: The green tab's data template was developed to process vertical casts located at a given location. *Longitude* and *latitude* must be input in cells 'B1:B2' in decimal format (degrees). *Longitude* can either be within the domain (-180º to 180º) or (0º to 360º) i.e., 10º 30' W can either be input as -10.5º or 349.5º. The *latitude* domain is (-90º to 90º) i.e., 30º S would be -30º. The input of the cast coordinates is essential, as *absolute salinity* is dependent of location (Sect 3.6).
- Pressure: *pressure* (p) units are dbar. For the upper ocean, 10 dbar ~ 10 m.
- Salinity: the salinity quantity is *practical salinity* (S_P) which continues to be the recommended salinity quantity to be archived (IOC, SCOR and IAPSO, 2010). *Practical salinity* (S_P) is obtained from conductivity and the EOS-80 polynomials for estimating S_P still apply. Oceanographic instruments that measure in-situ conductivity, output their measurements usually in *conductivity* – *temperature* - *pressure* triplets and so *conductivity* (mS cm^{-1}) might be archived instead of S_P. If this is the case, *conductivity* may be used as input data (column 'A') instead of *practical salinity*. Column 'F' of the spreadsheet ('S_P from C') checks if there are S_P data in column 'C' and if not, computes S_P from the conductivity data using the {*SP_from_C(C, t, p)*} function (note: EOS-80 polynomials use temperature IPTS-68 as argument, while TEOS-10 functions expect temperature to be ITS-90; for consistency, the temperature argument for this function is ITS-90 and the first line of code converts temperature back to IPTS-68).

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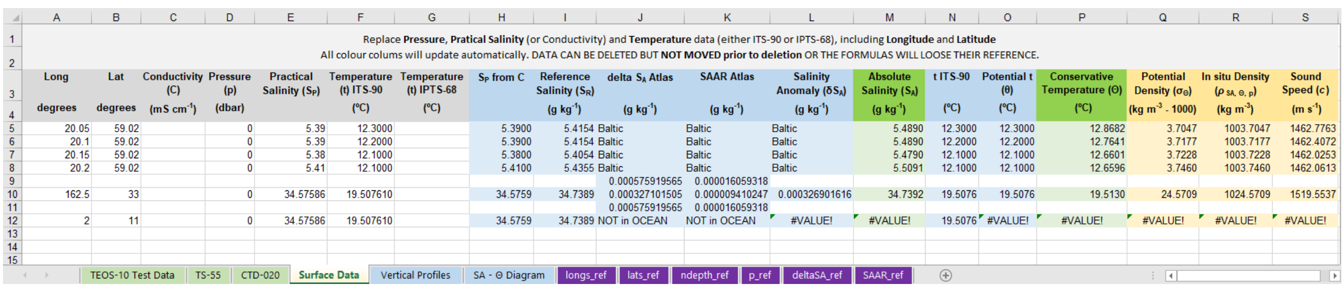
- Temperature: *temperature* (ºC) should be input in column 'D' or 'E', respectively if it is ITS-90 or IPTS-68 (data sets before 1990 are in the IPTS-68 standard, but recent data can still be using this standard instead of the newer ITS-90 – checking the instrument specifications and/or the metadata associated with the data is advisable). Column 'L' of the spreadsheet ('t ITS-90') either uses data in column 'D', if it exists, or converts the ITS-68 values to ITS-90 (ITS-90 = ITS-68 / 1.00024). All functions use temperature ITS-90 as input.

2.2 The yellow 'Surface data' tab

The yellow 'Surface data' tab content differs from the other data spreadsheets on what refers to the input of the location coordinates. In this spreadsheet, longitude and latitude are input in the first two columns, allowing in this way the assignment of distinct coordinates for each line. This is useful if the data set is not a vertical cast at a given location but a set of measurements on different locations, typically at the same pressure level (e.g., surface measurements). The data included are 'fictitious' and used here to demonstrate the use of the template. The location of the first four data lines is in the Baltic Sea. Conditions in the Baltic are different from the open ocean (McDougall, 2010) and TEOS-10 treats this adjacent sea as being a specific case – while for the world ocean the estimation of S_A depends on the measured salinity anomaly values at that location (look-up tables), for the Baltic it is estimated by Eq. (1).

$$S_A\ (Baltic) = \left(\frac{35.16504-0.087}{35}\right) \times S_P + 0.087 \qquad (1)$$

Whenever the location is in the Baltic (which is checked by the {*is_Baltic(lon, lat)*} function), the salinity anomaly cells display 'Baltic'. This spreadsheet also includes a line with data from line one of the 'TEOS-10 Test Data' tab (surface data from the NW Pacific) as well as a location over land, which returns 'NOT in OCEAN' for the look-up table cells, and an error for the other parameters.



Replace **Pressure, Pratical Salinity** (or Conductivity) and **Temperature** data (either ITS-90 or IPTS-68), including **Longitude** and **Latitude**
All colour colums will update automatically. DATA CAN BE DELETED BUT **NOT MOVED prior to deletion** OR THE FORMULAS WILL LOOSE THEIR REFERENCE.

	A	B	C	D	E	F	G	H	I
3	Long	Lat	Conductivity (C)	Pressure (p)	Practical Salinity (S_P)	Temperature (t) ITS-90	Temperature (t) IPTS-68	S_P from C	Reference Salinity (S_R)
4	degrees	degrees	(mS cm^{-1})	(dbar)		(ºC)	(ºC)		(g kg^{-1})
5	20.05	59.02		0	5.39	12.3000		5.3900	5.4154
6	20.1	59.02		0	5.39	12.2000		5.3900	5.4154
7	20.15	59.02		0	5.38	12.1000		5.3800	5.4054
8	20.2	59.02		0	5.41	12.1000		5.4100	5.4355
9									
10	162.5	33		0	34.57586	19.507610		34.5759	34.7389
11									
12	2	11		0	34.57586	19.507610		34.5759	34.7389
13									
14									
15									

	J	K	L	M	N	O	P	Q	R	S
3	delta S_A Atlas	SAAR Atlas	Salinity Anomaly (δS_A)	Absolute Salinity (S_A)	t ITS-90	Potential t (θ)	Conservative Temperature (Θ)	Potential Density (σ_Θ)	In situ Density ($\rho_{SA,\Theta,p}$)	Sound Speed (c)
4	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})	(ºC)	(ºC)	(ºC)	(kg m^{-3} - 1000)	(kg m^{-3})	(m s^{-1})
5	Baltic	Baltic	Baltic	5.4890	12.3000	12.3000	12.8682	3.7047	1003.7047	1462.7763
6	Baltic	Baltic	Baltic	5.4890	12.2000	12.2000	12.7641	3.7177	1003.7177	1462.4072
7	Baltic	Baltic	Baltic	5.4790	12.1000	12.1000	12.6601	3.7228	1003.7228	1462.0253
8	Baltic	Baltic	Baltic	5.5091	12.1000	12.1000	12.6596	3.7460	1003.7460	1462.0613
9	0.000575919565	0.000016059318								
10	0.000327101505	0.000009410247	0.000326901616	34.7392	19.5076	19.5076	19.5130	24.5709	1024.5709	1519.5537
11	0.000575919565	0.000016059318								
12	NOT in OCEAN	NOT in OCEAN	#VALUE!	#VALUE!	19.5076	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
13										
14										
15										

Figure 2: TEOS-10 EXCEL workbook 'Surface data' tab. Surface data from different locations (location coordinates for each line). Four samples are from the Baltic Sea, one from the NW Pacific and one location is over land.

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2.3 Vertical Profiles tab

The 'Vertical profiles' tab includes five plots that use the 'TS-55' and 'CTD-020' data sets and one plot with the 'TEOS-10 Test Data' data set. Two of these plots are reproduced in Figs. 3 and 4. Changing the data will update the plots accordingly, and the user can add extra profiles by right clicking the plot area, click 'Select Data' and edit/update the data sources.

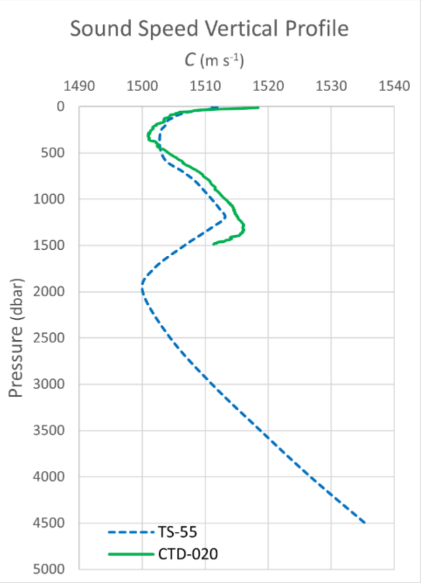

Figure 3: Sound speed vertical profile of two data sets included in TEOS-10 EXCEL. This plot is one of six included in the 'Vertical Profiles' tab.

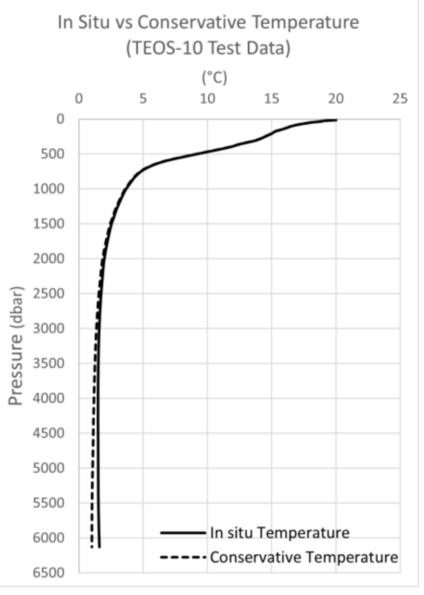

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Figure 4: Comparison between *in situ* and *conservative temperature* of the TEOS-10 Test Data included in TEOS-10 EXCEL. This plot is one of six included in the 'Vertical Profiles' tab.

2.4 S_A – Θ Diagram tab

This is a template for plotting *absolute salinity* (S_A) – *conservative temperature* (Θ) diagrams. Since the introduction of TEOS-10, S_A – Θ diagrams have replaced T-S diagrams (EOS-80) for the characterisation of water masses in the ocean. The two diagrams represented are from the NW Pacific ('TEOS-10 Test Data') and NE Atlantic ('TS-55'). Users can right-click the plot area, click 'Select Data' and edit/update the data sources. The plot also shows the pressure values at selected points along the two S_A – Θ diagram lines (the label of the points is retrieved from the pressure data column in the respective data tab). These points can be individually selected and edited. The density field is shown through a set of σ_Θ dashed lines obtained from S_A – Θ pairs that resolve to constant values of σ_Θ (i.e., 24, 25, …, 29). As in all data spreadsheets, white cells can be edited. In this case, S_A spans from the *x*-axis minimum (33.0) to the *x*-axis maximum (38.0) with a 0.05 increment. The *conservative temperature* (Θ) values (green columns) are obtained by the function {*sigma_CT_line(SA, sigma, min_temp, max_temp*}. If more σ_Θ lines are desired, additional column pairs can be inserted into the spreadsheet and new series added to the plot.

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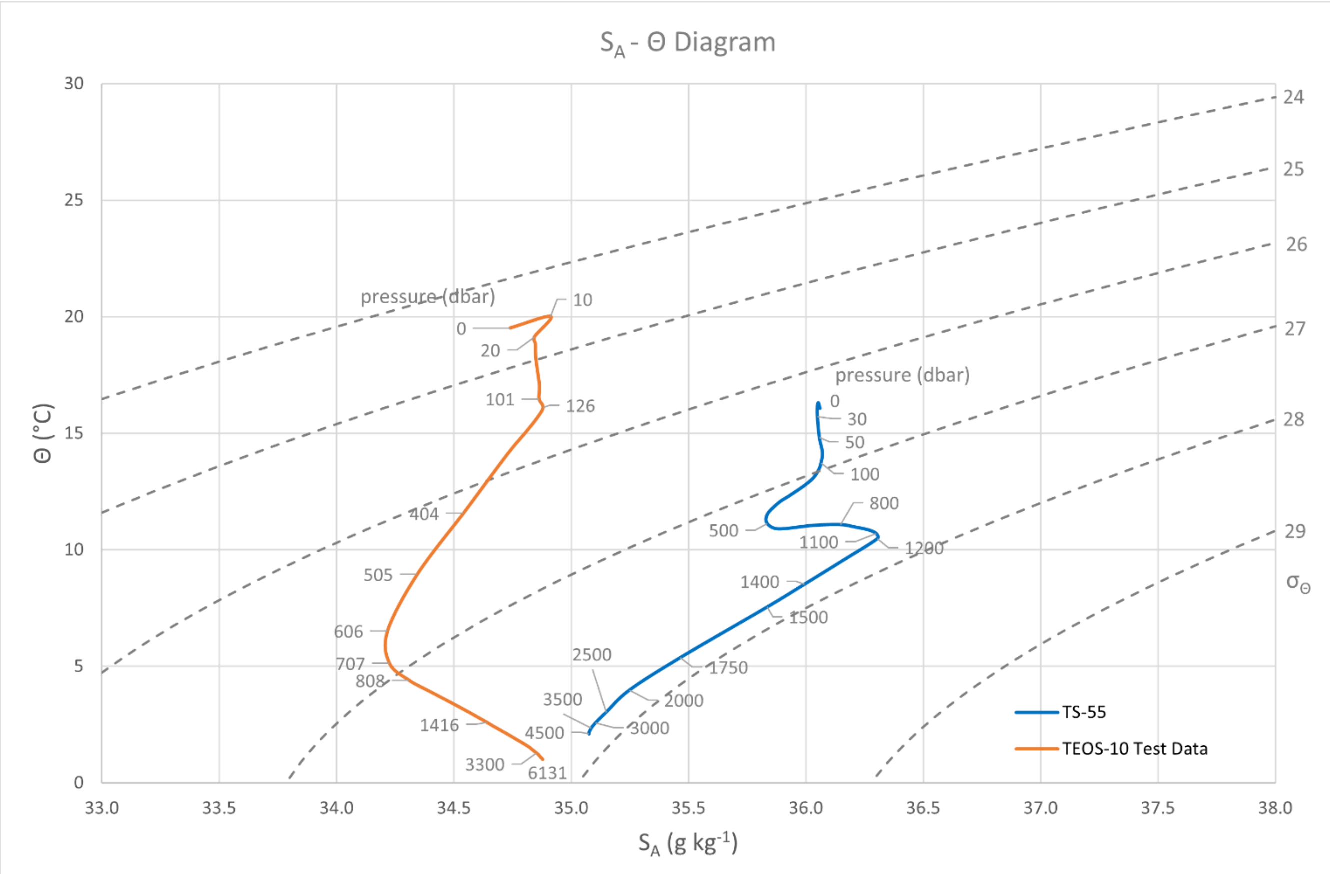

Figure 5: *Absolute salinity* (S_A) – *conservative temperature* (Θ) diagrams. Data are from the 'TEOS-10 Test Data' (NW Pacific) and 'TS-55' tab (NE Atlantic off the Iberian Peninsula). Pressure values are obtained dynamically from the data and the density field (σ_Θ) is computed from data included in the spreadsheet template.

2.5 The TEOS-10 Look-up tabs (purple) *aka* the 'Atlas'

Figure 6 shows the [ndepth_ref] look-up table which contains the number of pressure levels in each of the seawater samples that constitute the 'Atlas'. If looking closer to this spreadsheet, it becomes apparent that the empty cells represent land, and the 'white' shapes approximate to a map of the world land masses. The top of the spreadsheet is the South Pole, bottom is the North Pole, and the Greenwich Meridian (0º longitude) is at the left. *Longitude* is positive to the right, so actually the 'map' is a skewed mirror image of the earth surface. Nonetheless, mirrored continental shapes are identifiable. The *longitude* bins (or cells) are referenced in the [longs_ref] look-up table, so the *longitude* of the cell highlighted in green at the upper left of Fig. 6, which *x*-coordinate is 4 (fourth column), is 12º East (value at the fourth line of the [longs_ref] table). This cell is at line nine (*y*-coordinate = 9) of the [ndepth_ref] table (Fig. 6) which, looking up in the [lats_ref] table, corresponds to -54º of *latitude*. The green cell in Fig. 1, corresponds though to a reference cast located at 54º S, 12º E, with 41 pressure levels. These 41

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pressure levels correspond to the *pressure* values indicated in the [p_ref] table. The [p_ref] table has level 22 (1010 dbar) highlighted in green, as this 3D location is used and referenced as a debug point in the {*LookUp_atlas(table_name, p, lon, lat)}* function, that retrieves data from the *absolute salinity anomaly* [deltaSA_ref] and the *absolute salinity anomaly ratio* [SAAR_ref] look-up tables. The [ndepth_ref] table (Fig. 6) has 45 lines by 91 columns and so [deltaSA_ref] and [SAAR_ref] which have both the same size, have 4,095 columns (45 x 91) by 45 lines (pressure levels). An additional numbering line (which does not affect how data is located) was added to facilitate debugging. Position (column number) in these tables is given by Eq. (2).

$$Column = (x - 1) * nlat + y \qquad (2)$$

In Eq. (2), x is the longitude bin, y the latitude bin and *nlat* the number of latitude bins (45). For the 'green' cell (Fig. 1), $x=4$ and $y=9$ as mentioned before, so the anomaly data for this cell is located at column 144, line 22 (which corresponds to 1010 dbar) of the [deltaSA_ref] table. The reference *salinity anomaly* at 54º S, 12º E, 1010 dbar, is 0.008323162 g kg^{-1} (also highlighted in green).

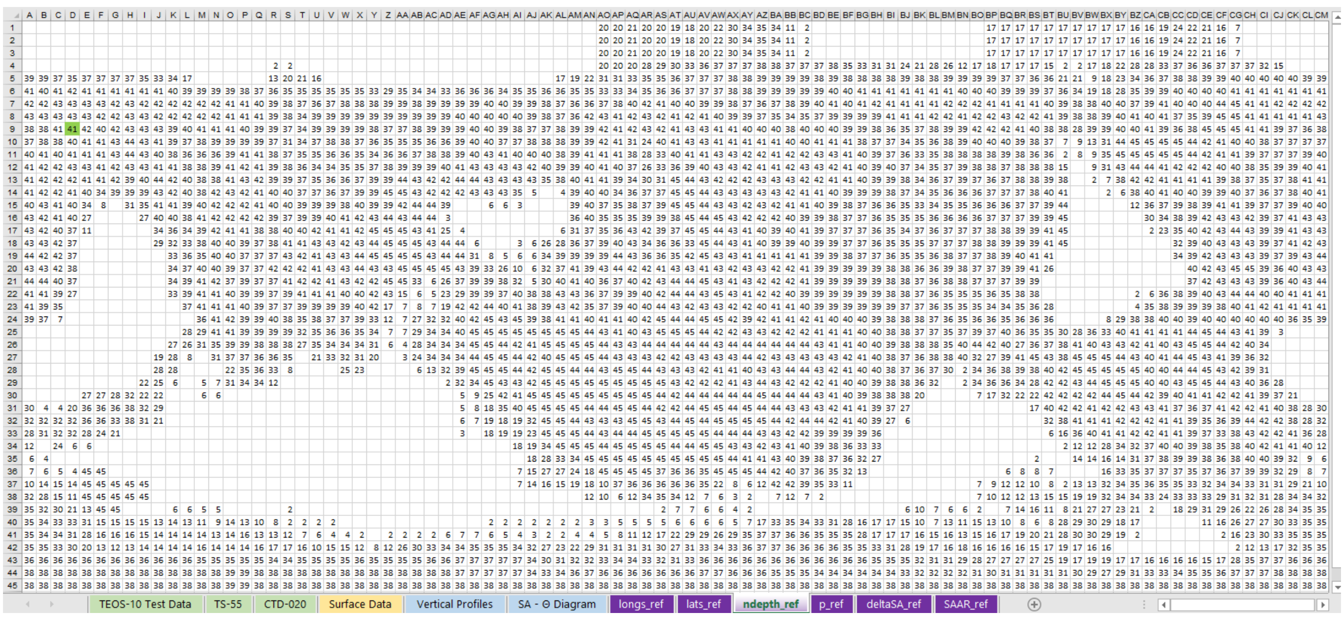

Figure 6: [ndepth_ref] look-up table. The table has 45 rows (latitude) by 91 columns (longitude). South is at the top (1st row is 86º S) and 1st column is 0º of longitude. The latitude x longitude grid is a 4º x 4º grid and each cell location is obtained from the [longs_ref] and [lats_ref] tables. Cell values are the number of *pressure* levels at the given location. The cell highlighted in green is used as a 'case study' in the text.

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3. VBA (Visual Basic for Applications) functions

Most functions of TEOS-10 EXCEL are a direct translation into VBA of the GSW MATLAB counterpart (McDougall and Barker, 2011) and the original credit and references were kept in the code comments. However, due to the different way matrices are handled in MATLAB versus VBA, some functions needed to be utterly redesigned, namely on what concerns accessing the 'Atlas' look-up tables. Returned values from TEOS-10 EXCEL are the same, for every parameter, as the ones obtained with the GSW toolbox, up to 15 decimal places, i.e., difference = 0.000000000000000 (error checking was performed against MATLAB GSW Toolbox version 3.06.12 from 25th May 2020). As referred before, access to the VBA project environment is obtained by pressing [Alt – F11]. All functions are described next, following the spreadsheet's column sequence.

3.1. S_P from C

Function {*SP_from_C (C, t, p)*} computes *practical salinity* (S_P) from conductivity using the EOS-80 Fofonoff and Millard (1983) equations. For consistency with all TEOS-10 functions, the temperature argument is ITS-90 (the first line of code converts temperature back to IPTS-68 as expected in EOS-80). *Practical salinity* is a dimensionless quantity, although PSU (Practical Salinity Units) is commonly used. For reference, the conductivity of Standard Sea Water at $S_P = 35$, $t_{68} = 15$, $p = 0$ is 42.9140 mS cm^{-1}, which can be used to validate the function.

3.2 Reference Salinity (S_R)

Reference salinity (S_R) is assumed to be proportional to *practical salinity* (IOC, SCOR and IAPSO, 2010) and obtained by Eq. (3). Units for S_R are g kg^{-1}.

$$S_R = \frac{35.16504}{35} \times S_P \qquad (3)$$

3.3 delta S_A Atlas

Function {*LookUP_atlas(table_name, p, lon, lat)*} interrogates the 'Atlas' database and was developed specifically for TEOS-10 EXCEL. The argument '*table_name*' can be one of the two look-up tables ("deltaSA_ref" or "SAAR_ref") and the returned values are a 3D interpolation of the 8 vertices of the cube around the location (Fig. 7). For the [deltaSA_ref] table, the result of the function is the atlas *absolute salinity anomaly* (δS_A^{atlas}). As the interpolation process is not very clearly described in the GSW toolbox documentation, it is discussed next.

3.3.1 Interpolation

Function {*LookUP_atlas(table_name, p, lon, lat)*} begins by finding the grid point P1 of the 3D cube around the location (Fig. 7). P1 would be the grid point immediately before the latitude and longitude of a given location. The same applies to pressure. For example, if the spreadsheet data cell corresponds to a cast located at 1100 dbar, +13º longitude, -51º latitude, the grid

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position of P1(lon*, lat*, p*) would be P1(4, 9, 22), obtained from the [longs_ref], [lats_ref] and [p_ref] tables. The other 8 points are referenced to P1, by adding one unit to the grid position of P1 as shown in Fig. 1.

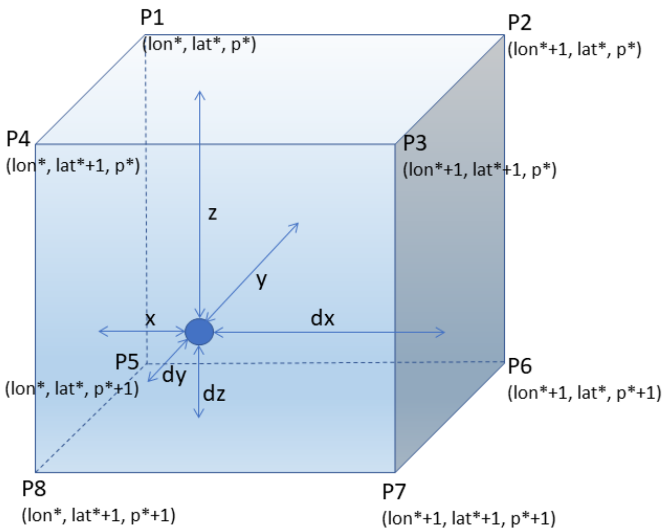

Figure 7: 3D interpolation cube. Points are defined by their grid position (lon*, lat*, p*).

The standard basic 3D interpolation model assumes that the cube dimensions are 1 x 1 x 1 (Bourke, 1999) and the distances *dx*, *dy* and *dz* are obtained by subtracting, respectively, *x*, *y*, and *z*, from the unit. However, in this case, the longitude and latitude grid space are 4º and the pressure difference between the upper and bottom points varies from grid level to grid level (e.g., 10 dbar between levels 1 and 2 but 101 dbar between levels 22 and 23). Distance *x*, *y* and *z* are obtained from Eqs. (4, 5 and 6), and then *dx*, *dy* and *dz* by Eq. (7)

$$x = (lon - lon(P1))/4 \quad (4)$$

$$y = (lat - lat(P1))/4 \quad (5)$$

$$z = (p - p(P1))/(p(P5) - p(P1)) \quad (6)$$

$$dx = 1 - x,\ \ dy = 1 - y,\ \ dz = 1 - z \quad (7)$$

The interpolated value (*v*) is obtained by weighing the contribution of the eight points according to Eqs. (8 to 16), where *v*(P*n*) is the δS_A^{atlas} value at P*n* (from [deltaSA_table]).

$$v1 = v(P1) \times dx \times dy \times dz \quad (8)$$

$$v2 = v(P2) \times x \times dy \times dz \quad (9)$$

$$v3 = v(P3) \times x \times y \times dz \quad (10)$$

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$$v4 = v(P4) \times dx \times y \times dz \qquad (11)$$

$$v5 = v(P5) \times dx \times dy \times z \qquad (12)$$

$$v6 = v(P6) \times x \times dy \times z \qquad (13)$$

$$v7 = v(P7) \times x \times y \times z \qquad (14)$$

$$v8 = v(P8) \times dx \times y \times z \qquad (15)$$

$$v = v1 + v2 + v3 + v4 + v5 + v6 + v7 + v8 \qquad (16)$$

3.3.2 Missing data

There are pressure levels in the atlas reference casts where data is missing. Figure 8 illustrates this situation.

	G	H	I	J	K	L	M	N	O	P	Q	R
23	0.009218692	0.008908996	0.00759247	0.005709105	0.004574747	0.003644211	0.003208049	0.003031175	0.00349246	0.003986676	0.003968637	0.004115448
24	0.009233077	0.008972897	0.007761753	0.005780614	0.004753488	0.004032915	0.003684931	0.003560448	0.003808101	0.003997765	0.003876938	0.003981588
25	0.009249478	0.009033516	0.007911187	0.005844102	0.004886662	0.004367845	0.004065591	0.00396472	0.003978199	0.003921243	0.003732477	0.003787497
26	0.00925642	0.009087358	0.008098981	0.005932269	0.00497313	0.004602549	0.004352101	0.004216718	0.004038171	0.003810867	0.003586259	0.00359505
27	0.009258621	0.009120991	0.008237284	0.006021737	0.005026371	0.004782731	0.00458536	0.004400239	0.00401516	0.003677485	0.003438529	0.003469429
28	0.009248313	0.009169287	0.008541587	0.006386436	0.005105027	0.004895867	0.004721168	0.004429583	0.003842076	0.003487118	0.003261295	0.003335104
29	0.009245437	0.009196107	0.008768696	0.006796146	0.005237766	0.004803792	0.004612022	0.004309108	0.003815922	0.003634408	0.003400565	0.003466424
30	0.009226827	0.009208929	0.008945121	0.007129832	0.005488165	0.004770552	0.004442442	0.004210304	0.003888642	0.003889622	0.003755912	0.0038033
31	0.009197872	0.009206341	0.009035997	0.007610069	0.005890486	0.004872129	0.004405444	0.004180367	0.00394193	0.004112428	0.004104743	0.004197571
32	0.009170239	0.009187315	0.009141968	0.007932154	0.006315794	0.005045773	0.004471019	0.004192354	0.003957406	0.00424212	0.004378315	0.004611299
33	0.00913718					0.005321122	0.004571465	0.004236636	0.003977235	0.004339081	0.004612237	0.004979521
34	0.009109314					0.005831923	0.004945996	0.004390707	0.004032286	0.004419669	0.004770676	0.005217486
35	0.00908662	0.009045589	0.00913435	0.008461061	0.00765709	0.00638616	0.005509364	0.004780258	0.004146816	0.004491119	0.004894749	0.005350943
36	0.009041758	0.008978659	0.009089345	0.008494994	0.007976087	0.007045019	0.006425593	0.005681561	0.004481928	0.004559633	0.004962076	0.005420412
37	0.008951321	0.008872803	0.009039996	0.008480566	0.008165775	0.007627993	0.007342053	0.006830766	0.005038608	0.004740746	0.005007445	0.005467756
38	0.008820467	0.008753362	0.009175537		0.008282431	0.007790812	0.007626658	0.007408762	0.005235964	0.004810099	0.005035742	0.005505476
39	0.008768482	0.00867393			0.008292218	0.007935395	0.007805511	0.007774958	0.005151711	0.00504291	0.005070624	0.005536356
40	0.008739336	0.008706534			0.008598181	0.007909775	0.007863286	0.007845305	0.00539689	0.005264025	0.005140008	0.005569826
41	0.008702934	0.008686641				0.007908649	0.007888701	0.007852586		0.005455169	0.005213869	0.005591903
42	0.008659186	0.008640046								0.004816461	0.00509936	0.005612582
43		0.008632253								0.00469658	0.005234804	0.005692186
44												
45												
46	7	8	9	10	11	12	13	14	15	16	17	18

TEOS-10 Test Data | TS-55 | CTD-020 | Surface Data | Vertical Profiles | SA - Θ Diagram | longs_ref | lats_ref | ndepth_ref | p_ref | deltaSA_ref | SAAR ...

Figure 8: [deltaSA_ref] table: reference data missing for pressure levels 33 and 34 of columns 8, 9, 10 and 11.

The GSW toolbox fills these gaps by averaging the neighbouring four points in the grid at the same pressure level. As the ocean is horizontally stratified, this makes 'oceanographic sense', but neighbour points, themselves, might also lack data at the same level, which might compromise the result. A $\delta S_A{}^{atlas}$ plot from [deltaSA_ref] column 8 (0º lon, -54º lat) is shown in Fig. 9. The $\delta S_A{}^{atlas}$ output of GSW toolbox and TEOS-10 EXCEL is the same for the part where there are data (blue line), but the output of the GSW toolbox for the two pressure levels where data is missing is clearly off the profile (orange). In this situation, TEOS-10 EXCEL implements a vertical interpolation within the vertical profile, which resolves better the missing data situations (green in Fig.9). The second case where GSW toolbox seems to be less consistent, is when not all points of the 3D interpolation cube exist at the last pressure level. The GSW toolbox test data (included in the 'TEOS-10 Test Data' tab) is such an example (Fig. 10). The GSW toolbox approach for resolving missing data on the last pressure level is as before. In these situations, if one of the four bottom points of the interpolation cube (P5, P6, P7 or P8 in Fig. 7) is missing, TEOS-10

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EXCEL assigns to it the same value of the next upper point at that location (e.g., *v*(P7) = *v*(P3)). Again, the resulting profile is
270 more coherent in TEOS-10 EXCEL than in the GSW toolbox (Fig. 10).

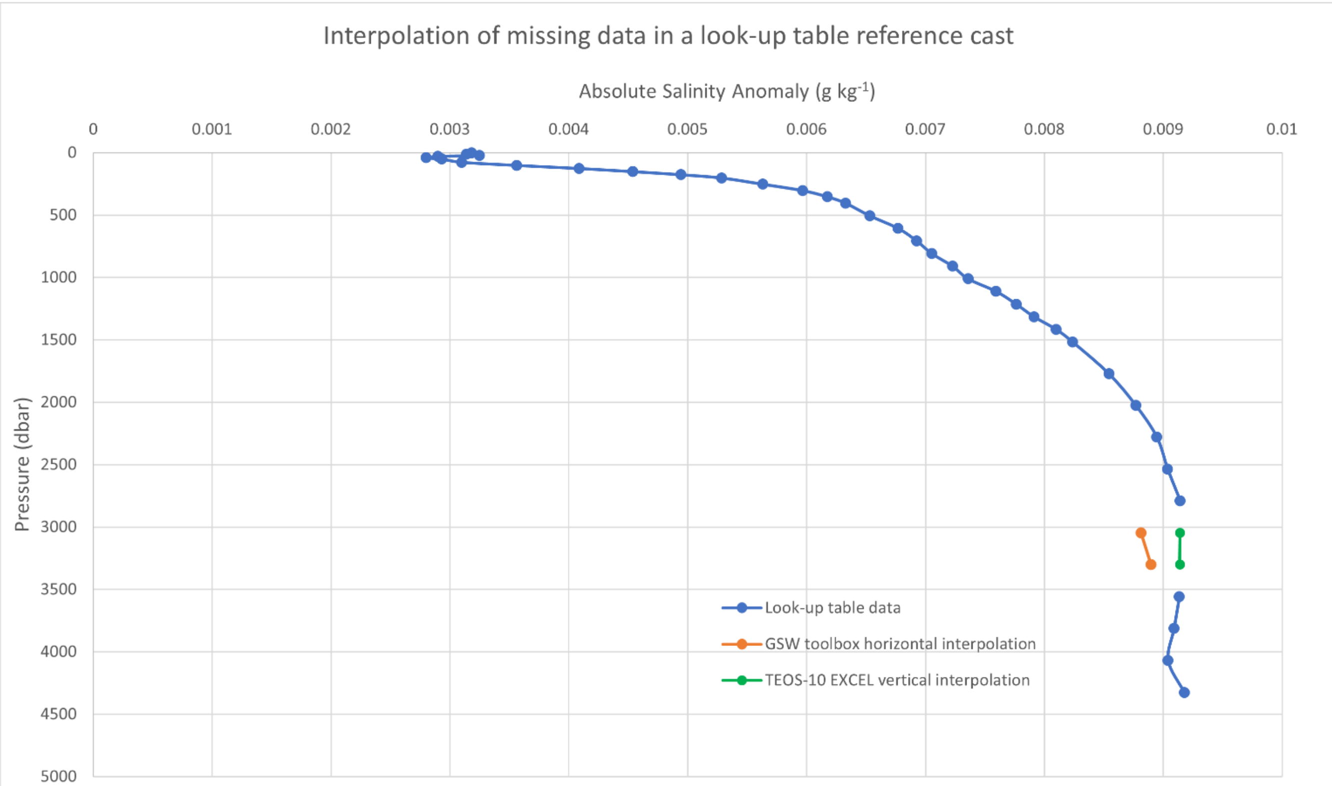

Figure 9: δS_A^{atlas} plot from [deltaSA_ref] column 8. Missing data at levels 33 and 34 (3045 and 3300 dbar) is not well resolved by horizontal interpolation (GSW toolbox). Vertical interpolation implemented in TEOS-10 EXCEL resolves better these situations.

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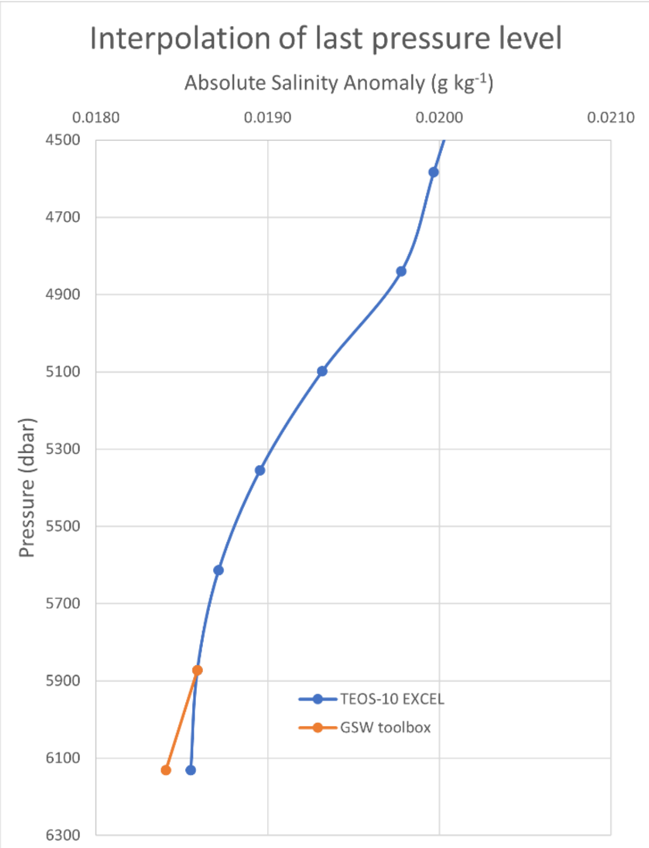

Figure 10: $\delta S_A{}^{atlas}$ plot from 'TEOS-10 Test Data' tab. Not all neighbour points have data at the last pressure level. For these points, TEOS-10 EXCEL uses the same value as of their last pressure level to resolve the 3D interpolation cube, while the GSW toolbox averages the same level data from neighbouring points.

3.4 delta SAAR Atlas

The atlas *absolute salinity anomaly ratio* (R^δ) is obtained by the function {*LookUP_atlas(table_name, p, lon, lat)*}, exactly as for the atlas *absolute salinity anomaly* (Sect. 3.3), but calling it with "SAAR_ref" as the *table_name* argument. R^δ is the quantity used to estimate *absolute salinity anomaly* (Sect. 3.5) which is then used for obtaining *absolute salinity* (Sect. 3.6).

3.5 Absolute Salinity Anomaly

Absolute s*alinity anomaly* (δS_A) is the product of the atlas *absolute salinity anomaly ratio* by *reference salinity* (Eq. 17).

$$\delta S_A = R^\delta \times S_R \qquad (17)$$

3.6 Absolute Salinity

Absolute salinity (S_A) is the sum of *reference salinity* and *salinity anomaly* (Eq. 18).

$$S_A = S_R + \delta S_A \quad (\text{g kg}^{-1}) \qquad (18)$$

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If the location is in the Baltic Sea, the world atlas salinity anomalies do not apply (McDougall, 2010) and *absolute salinity* is computed algebraically from *practical salinity* with function {*SA_Baltic(SP)*}, which applies Eq. (19).

$$S_A^{Baltic} = \frac{(35.16504-0.087)}{35} \times S_P + 0.087 \quad (\text{g kg}^{-1}) \qquad (19)$$

Limits for the Baltic were taken from Fig. 2 of Feistel et al. (2010). Function {*is_Baltic(lon, lat)*} checks if the location is in the Baltic Sea by finding if the coordinates lie within any of two rectangular areas defined by [9º E : 15º E; 52º N : 60º N] and [15º E : 30º E; 52º N : 67º N].

3.7 Temperature ITS-90

The temperature standard used in TEOS-10 for temperature measurements is ITS-90 (Preston-Thomas, 1990). If column 'D' of the data spreadsheet (temperature ITS-90) contains data, these values will be used, if the input temperature is IPTS-68 (column 'E'), it will be converted to ITS-90 using Eq. (20).

$$t_{ITS-90} = {t_{IPTS-68}}/{1.00024} \quad (^{\circ}\text{C}) \qquad (20)$$

3.8 Potential Temperature (*θ*)

Potential temperature (θ, ºC) is obtained by function {*pt0_from_t(SA,t,p)*}. Three other functions, {*Entropy_part(SA, t, p)*}, {*Entropy_part_zerop(SA, pt0)*}, {*Gibbs_pt0_pt0(SA, pt0)*} are called within the computation process. These four functions are a VBA translation of the original GSW toolbox counterparts (IOC, SCOR and IAPSO, 2010; McDougall and Wotherspoon, 2013).

3.9 Conservative Temperature (Θ)

Conservative temperature (Θ, ºC) is the temperature quantity used as argument in the Thermodynamic Equation Of Seawater - 2010 (IOC, SCOR and IAPSO, 2010). It is obtained with function {*CT_from_pt(SA, pt)*} which is a direct translation from the GSW toolbox counterpart and estimates Θ from S_A and θ.

3.10 Potential Density (σ_Θ)

Potential density (σ_Θ, kg m^{-3} - 1000) with reference to sea pressure of 0 dbar is estimated by function {*sigma0(SA, CT)*}, which arguments are *absolute salinity* (S_A) and *conservative temperature* (Θ). This function uses the TEOS-10 75-term equation and is a VBA translation of the original GSW toolbox counterpart (IOC, SCOR and IAPSO, 2010; McDougall et al., 2003; Roquet et al., 2015).

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3.11 In situ Density ($\rho_{S_A,\ \Theta,\ p}$)

In situ density ($\rho_{S_A,\ \Theta,\ p}$, kg m^{-3}) is estimated by function {*rho(SA, CT, p)*}, which arguments are *absolute salinity* (S_A), *conservative temperature* (Θ) and *pressure* (p). This function uses the TEOS-10 75-term equation and is a VBA translation of the original GSW toolbox counterpart (IOC, SCOR and IAPSO, 2010; McDougall et al., 2003; Roquet et al., 2015).

3.12 Sound speed (c)

Sound speed (c, m s^{-1}) is estimated by function {*Sound_Speed(SA, CT, p)*}, which arguments are *absolute salinity* (S_A), *conservative temperature* (Θ) and *pressure* (p). This function uses the TEOS-10 75-term equation and is a VBA translation of the original GSW toolbox counterpart (IOC, SCOR and IAPSO, 2010; McDougall et al., 2003; Roquet et al., 2015).

3.13 [deltaSA_ref] table not needed!

The atlas *absolute salinity anomaly* (column 'H' of the data spreadsheets) is not used for any calculation, as *absolute salinity anomaly* (δS_A) is obtained from the product of *absolute salinity anomaly ratio* (R^δ) by *reference salinity* (Eq. 17), and R^δ is retrieved from the [SAAR_ref] look-up table. The [deltaSA_ref] look-up table is though not necessary for any computation and can eventually be deleted from the EXCEL workbook to lighten up the code. However, this table was used as a debugging tool in the development of the VBA functions, and the error checking and interpolation improvements described in Sect. (3.3) refer to this atlas table, reason why it was opted to include it in this first version of TEOS-10 EXCEL as a supporting element for this paper. Additionally, users might have interest in ascertaining the atlas *absolute salinity anomaly* for a given location or perform further error checking, comparing TEOS-10 EXCEL output against GWS toolbox for other data sets.

4. Conclusions

To our knowledge, TEOS-10 EXCEL is the first implementation of the Thermodynamic Equation Of Seawater – 2010 outside the official GSW toolboxes. It does not aim, by any mean, to reproduce the full-featured GSW environment as it implements only a small subset of TEOS-10 functions. However, opening the possibility of estimating a relevant set of seawater parameters within a well-known and friendly environment (EXCEL), will hopefully democratise the compliance with current oceanographic standards among a large community of researchers and students who are not at ease with the use of high-level programming languages. As discussed in the paper, some issues were detected with the GSW interpolation when there is missing data in the atlas reference tables. In these cases, TEOS-10 EXCEL adopts an alternative approach to the interpolation method, which has produced better results (Sect. 3.3.2). Nonetheless, this is perhaps a situation that deserves further research.

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Code and data availability

TEOS-10 EXCEL is available for download at https://doi.org/10.5281/zenodo.4763574

Author Contribution

CG Martins developed the code, tested the data, and prepared the original draft. J Cross critically reviewed and edited the initial version of the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

References

Bosse, Y. and Gerosa, M.A.: Why is programming so difficult to learn? Patterns of Difficulties Related to Programming Learning Mid-Stage, ACM SIGSOFT, 41(6), 1-6, https://doi.org/10.1145/3011286.3011301, 2017.

Bourke, P.: Interpolation methods, http://paulbourke.net/miscellaneous/interpolation/, 1999, last access 11 January 2022.

Buzzetto-More, N.A., Ukoha, O., and Rustagi, N.: Unlocking the barriers to women and minorities in computer science and information systems studies: Results from a multi-methodical study conducted at two minority serving institutions, JITE-Research, 9(1), 115-131, https://www.learntechlib.org/p/111359/, 2010.

Feistel, R., Weinreben, S., Wolf, H., Seitz, S., Spitzer, P., Adel, B., Nausch, G., Schneider, B., and Wright, D.G.: Density and absolute salinity of the Baltic Sea 2006–2009, Ocean Sci., 6(1), 3-24, https://doi.org/10.5194/os-6-3-2010, 2010.

Fofonoff, N.P. and Millard Jr., R.C.: Algorithms for computation of fundamental properties of seawater, UNESCO R. M., 44, UNESCO, 53 pp., http://hdl.handle.net/11329/109, 1983.

Gibbs, J.W.: On the equilibrium of heterogeneous substances, Trans. Conn. Acad. Arts Sci., 3, 108–248, 343–524, https://archive.org/details/transactionsconn03conn/page/108/mode/2up?view=theater, 1874–1878, last access 11 January 2022.

IOC, SCOR and IAPSO: The international thermodynamic equation of seawater – 2010: Calculation and use of thermodynamic properties, IOC Tech. S., 56, UNESCO, 196 pp., http://www.teos-10.org/pubs/TEOS-10_Manual.pdf, 2010.

Levitus, S.: Climatological Atlas of the World Ocean, NOAA Prof. Paper, 13, NOAA, 173 pp., 1982.

Martins, C.G.: OCEANUS: um Atlas Digital Oceanográfico aplicado ao estudo da Estrutura, Variabilidade e Climatologia do Atlântico ao largo de Portugal Continental, Ph.D. thesis, Universidade de Lisboa, 348 pp., 1998.

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

McDougall, T.J. and Wotherspoon, S.J.: A simple modification of Newton's method to achieve convergence of order 1+ 2, Appl. Math. Lett., 29, 20-25, https://doi.org/10.1016/j.aml.2013.10.008, 2014.

McDougall, T.J., Jackett, D.R., Millero, F.J., Pawlowicz, R., and Barker, P.M.: A global algorithm for estimating Absolute Salinity, Ocean Sci., 8(6), 1123-1134, https://doi.org/10.5194/os-8-1123-2012, 2012.

McDougall, T.J., Jackett, D.R., Wright, D.G., and Feistel, R.: Accurate and computationally efficient algorithms for potential temperature and density of seawater, J. Atmos. Ocean. Tech., 20(5), 730-741, https://doi.org/10.1175/1520-0426(2003)20%3C730:AACEAF%3E2.0.CO;2, 2003.

Millero, F.J.: History of the equation of state of seawater, Oceanography, 23(3), 18-33, https://www.jstor.org/stable/24860883, 2010.

Preston-Thomas, H.: The International Temperature Scale of 1990 (ITS-90), Metrologia, 27(1), 3-10, https://d1.amobbs.com/bbs_upload782111/files_15/ourdev_444609.pdf, 1990.

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