Salinity Determination from Use of CTD Sensors

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ABSTRACT

To convert the specific conductance $C(S,t,p)$ measured by an *in situ* CTD sensor to salinity in a manner consistent with the international standard expression proposed by Cox *et al.*, it is necessary to have established a means of estimating the specific conductance of seawater having a salinity of 35‰, [i.e., $C(35,t,0)$]. Third-order polynomial expressions formulated from samples having salinities near 35‰ are discussed. From the results of this study, it is recommended that an international expression for $C(35,t,0)$ be established and that the conductivity ratio R_t calculated from this standard expression be used to obtain salinity using the UNESCO tables or the equation of Cox *et al.*

1. Introduction

There are many investigators who for a variety of reasons still measure specific conductance $C(S,t,p)$ using *in situ* conductivity-temperature-depth (CTD) sensors as a means of determining the salinity of seawater. A problem arises, however, when an attempt is made to relate the $C(S,t,p)$ measured by this sensor to its corresponding value of salinity, because the widely accepted expression of salinity as a function of conductivity proposed as the international standard by Cox *et al.* (1967) and as discussed by Wooster *et al.* (1969), Lyman (1969) and Tsurikova and Tsurikov (1971) is based upon the use of R_t [defined as the ratio of the specific conductance $C(S,t,0)$ of a seawater sample to that of water having a salinity S of exactly 35‰, where both samples are at the same temperature t, and under a pressure of one standard atmosphere], i.e.,

$$R_t = C(S,t,0)/C(35,t,0). \qquad (1)$$

The UNESCO tables and Cox *et al.*'s polynomial expression are actually for R_{15}, so they also provide a correction to R_t for temperatures different from $t=15$C.

For shallow waters where pressure effects are minimal,

$$C(S,t,p) \approx C(S,t,0), \qquad (2)$$

and $C(S,t,p)$ can be used directly to calculate (1), provided, of course, that $C(35,t,0)$ is known. For depths where pressure is important, Bradshaw and Schleicher (1965), Perkin and Walker (1972) (for arctic regions) and Hassler (1971) have discussed methods that can be used to compensate for its effects.

Clearly, if one measures $C(S,t,p)$ and wants to use Cox's standard expression, what is needed is a reliable and standard way to approximate $C(35,t,0)$. Furthermore, since Copenhagen Normal Water is the standard used in determining salinity and specifically, since all conductivity salinometers use it to measure the reference value of $C(35,t,0)$ and calculate R_t, the same standard should be used in providing $C(35,t,0)$ for use with *in situ* CTD sensors. What is needed, therefore, is a complete set of conductivity measurements for Copenhagen Normal Water over a wide range of temperatures and an equation and table to approximate $C(35,t,0)$ that fits these data.

2. Approximating C(35, t, 0)

Most of the empirical relationships formulated specifically to approximate $C(35,t,0)$ have been published in technical reports or included in the proceedings of conferences and, therefore, have been generally unavailable for use by other investigators.

In almost every instance the formulations were based upon the experimental work of either Thomas *et al.* (1934), Brown and Allentoft (1966), or Cox *et al.* (1967). Actually, the intent of the latter two studies was to measure the conductivity ratio R_t and not the specific conductance $C(35,t,0)$ directly, but valid approximation expressions can be derived from the data. Other studies (Weyl, 1964; Park and Burt, 1965) have discussed some of the possible errors in the data of Thomas *et al.* (1934).

One recently published paper that has had a wide distribution is that of Perkin and Walker (1972). They developed a third-order polynomial equation to estimate $C(35,t,0)$ from the experimental data of Brown and Allentoft (1966), but their intent was to provide an approximation technique for use in the Arctic so their equation is not valid for temperatures greater than 25C.

TABLE 1. Comparison of results of four equations for approximating the conductivity of seawater that has a salinity of 35‰.

	Conductances (mΩ^{-1} cm^{-1})				Differences ($\times 10^{-2}$ mΩ^{-1} cm^{-1})					
T (°C)	KR	PW	KN_1	KN_2	KR−PW	KN_1-KN_2	KR−N_1	KR−KN_2	KN_1−PW	KN_2−PW
35	63.7274	63.7927*	63.7374	63.7508	−6.53*	−1.34	−1.00	−2.34	−5.53*	−4.19*
30	58.3324	58.3740*	58.3399	58.3493	−4.16*	−0.94	−0.75	−1.67	−3.41*	−2.47*
25	53.0499	53.0779	53.0555	53.0637	−2.80	−0.82	−0.56	−1.38	−2.24	−1.42
20	47.9003	47.9216	47.9044	47.9133	−2.13	−0.89	−0.41	−1.30	−1.72	−1.83
15	42.9040	42.9225	42.9069	42.9170	−1.85	−1.01	−0.29	−1.30	−1.56	−0.55
10	38.0814	38.0975	38.0833	38.0941	−1.61	−1.08	−0.19	−1.27	−1.42	−0.34
5	33.4529	33.4640	33.4538	33.4635	−1.11	−0.97	−0.09	−1.06	−1.02	−0.05
0	29.0390	29.0392	29.0386	29.0443	−0.02	−0.57	+0.04	−0.53	−0.06	−0.51

Symbol	Data source	Range of fit (°C)	rms deviation of fit (mΩ^{-1} cm^{-1})	chlorinity (‰)
KR	Reeburgh—Red Sea	$0 \leqslant t \leqslant 35$	0.00013	19.374
KN_1	Reeburgh—Normal Water	$-1 \leqslant t \leqslant 35$	0.00100	19.369
KN_2	Reeburgh—Normal Water	$-1 \leqslant t \leqslant 35$	0.00212	19.372
PW	Perkin and Walker (Brown and Allentoft)	$0 \leqslant t \leqslant 25$		19.373

$$KN_1 = 29.04433 + 0.86141t + 0.46109\mathrm{X}10^{-2}\, t^2 - 0.2545\mathrm{X}10^{-4}\, t^3$$

* Beyond range of fit.

Needing an interim expression to approximate $C(35,t,0)$ for temperatures greater than 25C, Knowles (1973a) formulated a third-order polynomial equation from Reeburgh's (1965) Red Sea data (interpolated to Cl = 19.374‰).

In the present analysis the results of this expression are compared with similar expressions formulated by Knowles (1973b) from Reeburgh's (1965) Normal Sea Water data (Cl = 19.369‰ and Cl = 19.372‰), and that formulated earlier by Perkin and Walker (1972). The results are included in Table 1.

TABLE 2. Comparison of empirical relationships for estimating $C(35, t, 0)$ at $t = 15$C.*

Author and source of data	C(35, 15, 0) (mΩ^{-1} cm^{-1})
Knowles (1973a, b)	
KR (Reeburgh Red Sea)	42.904
KN_1 (Reeburgh Normal Water)	42.907
KN_2 (Reeburgh Normal Water)	42.917
Perkin and Walker (1972) (Brown and Allentoft)	42.923
Rohde (quoted by Keyte, 1970) (Thomas *et al.*)	42.899
Ribe and Howe (1967) (Cox *et al.* and Brown and Allentoft)	42.917
Bennett (quoted by Greenburg, 1972)	42.929
ZDLP (Zaburdaev *et al.*, 1969) (Cox *et al.*)	42.896
Accerboni and Mosetti (1967) (Cox *et al.* and Brown and Allentoft)	42.902
Daniel and Collias (1971) (Thomas *et al.*)	42.698

* Includes results from Walker and Chapman (1973).

Perkin and Walker's specific conductance values are under the heading PW; KR, KN_1 and KN_2 come from Knowles polynomial using the coefficients computed from Reeburgh's Red Sea data and his Normal Sea Water data (Cl = 19.369‰ and Cl = 19.372‰), respectively. Those values marked with an asterisk are for temperatures beyond the range of fit of the equation and show the danger of extrapolation beyond that range.

Since the equation developed by Perkin and Walker (PW) also used Reeburgh's Red Sea data for $t = 0$C, it is not surprising that the least difference with KR occurs at this temperature. A systematic increase in the differences is evident for $t > 0$C, which is probably a function of the different set of data used in each case.

A comparison of the Normal Water values of KN_1 minus KN_2 indicates a non-systematic fluctuation in differences, which may, in part, be because only one set of conductivity measurements was made as a function of temperature for each Normal Water sample. Indeed, if the rms deviation of fit for each of these two data sets (as shown in Table 1) is examined, there is a strong indication that the measurements of KN_2 may not have been as precise as those of KN_1. The differences, however, when rounded to the nearest hundredth of a millimho per centimeter (mΩ^{-1} cm^{-1}) are all 0.01 mΩ^{-1} cm^{-1} greater for KN_2 than for KN_1, which is consistent with the fact that the salinity of KN_2 is 0.006‰ greater than KN_1. This difference of 0.01 mΩ^{-1} cm^{-1} is probably significant only for the best CTD units that have an accuracy greater than ±0.01 mΩ^{-1} cm^{-1}.

A comparison of KR and PW with the two Normal Water samples KN_1 and KN_2 show differences that range from as small as 0.0004 mΩ^{-1} cm^{-1} (for KR−KN_1

at $t=0C$) to as large as -0.0224 mΩ^{-1} cm^{-1} (for KN_1-PW at $t=25C$) and -0.0234 mΩ^{-1} cm^{-1} (for $KR-KN_2$ at $t=35C$), the latter two differences being significantly large. Generally $KR-KN_1$ was markedly less than KN_1-KN_2 and $KR-KN_2$ was just slightly larger in magnitude, indicating that though Red Sea Water cannot be considered characteristic of normal oceanic water and the results must be used with extreme caution, diluted to 35‰ salinity it is not significantly unlike it in terms of specific conductance.

A study with a wider ranging comparison of salinity-conductivity formulas was made by Walker and Chapman (1973). Some of their results are included in Table 2, which presents values of $C(35,15,0)$ obtained from the various $C(35,t,0)$ formulas for $t=15C$. An examination of the table indicates differences even for formulas derived from the same data source. All but one of the values lie within the range 42.896 mΩ^{-1} cm^{-1} $\leqslant C(35,15,0)\leqslant 42.929$ mΩ^{-1} cm^{-1} which indicates also the variability in salinity ($\sim$0.03‰) that could result from the use of these different formulas.

3. Conclusions

The results of this study re-emphasize the conclusion made earlier (Knowles, 1973a), i.e., that there is a need to have established a standard expression for the estimation of $C(35,t,0)$ for use with CTD sensors. To make it most consistent with current salinity analysis techniques using conductive salinometers and applicable at any latitude, this expression should be derived from a series of measurements made on samples of Copenhagen Normal Water with a chlorinity near 19.374‰ over the temperature range -1 to 40C. To establish it as an international standard, the measurements should be under the supervision of the appropriate UNESCO committee.

It is also recommended that the conductivity ratio R_t calculated from this standard expression be used to obtain salinity using the UNESCO tables or the equation of Cox *et al.* (1967). Instrument differences and measurements made in non-standard composition seawater will still introduce errors as is the case for other techniques, but with a standard expression for $C(35,t,0)$ at least one more variable will have been minimized.

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REFERENCES

Accerboni, E., and F. Mosetti, 1967: A physical relationship among salinity temperature and electrical conductivity of seawater. *Boll. Geofis. Teor. Appl.*, **9**, No. 34, 87–96.

Bradshaw, A., and K. E. Schleicher, 1965: The effect of pressure on the electrical conductance of seawater. *Deep Sea Res.*, **12**, 151–162.

Brown, N. L., and B. Allentoft, 1966; Salinity, conductivity and temperature relationship of seawater and over the range 0–50 PPT. Final Report, ONR Contract NOnr 4290 (00) M.J.O. No. 2003, Bissett-Berman, San Diego, Calif.

Cox, R. A., F. Culkin and J. P. Riley, 1967: The electrical conductivity/chlorinity relationship in natural seawater. *Deep Sea Res.*, 14, 203–220.

Daniel, R. A., and E. E. Collias, 1971: Inductive conductivity probe calibration. *Proc. IEEE Intern. Conf. Engineering in the Oceanic Environment*, San Diego, Calif., 21–23 September, 16–18.

Greenberg, D. A., 1972: Comparisons of salinity formulae used in Canada. Canada Oceanic Data Centre, M.S.B., Dept. of Environment, 25 pp.

Hassler, B. V., 1971: The temperature-pressure dependence of ionic conductivity in sea water at temperatures in the oceanic range. M.S. thesis, U.S. Naval Postgraduate School.

Keyte, F. K., 1970: Processing of STD magnetic tapes. B.I. Computer Note 1970-9-C, Bedford Institute Atlantic Oceanographic Lab., Dartmouth, N.S., Canada.

Knowles, C. E., 1973a: Salinity determination for use with CTD sensors (abstract). *Trans. Amer. Geophys. Union*, **54**, 300.

——, 1973b: CTD sensors, specific conductance and the determination of salinity. Rept. No. 73-3, NCSU Center for Marine and Coastal Studies; also Office of Sea Grant, Rept. No. UNC-SG-73-16, 15 pp.

Lyman, John, 1969: Redefinition of salinity and chlorinity. *Limnol. Oceanogr.*, **14**, 928–929.

Park, K., and W. V. Burt, 1965: Electrolytic conductance of seawater and the salinometer. *J. Ocean. Soc. Japan*, Part 1, **21**, No. 2, 69–80; Part 2, **21**, No. 3, 124–132.

Perkin, R. G., and E. R. Walker, 1972: Salinity calculations from *in situ* measurements. *J. Geophys. Res.*, **77**, 6618–6621.

Reeburgh, W. S., 1965: Measurements of electrical conductivity of seawater. *J. Marine Res.*, **23**, 187–199.

Ribe, R. L., and J. G. Howe, 1967: An empirical equation relating seawater salinity, temperature, pressure and electrical conductivity. Unpublished report, Oceanographic Instrumentation Center, Naval Oceanographic Office, Washington, D.C.

Thomas, B. D., T. G. Thompson and C. L. Utterback, 1934: The electrical conductivity of seawater. *J. Cons. Perman. Intern. Explor. Mer*, **9**, 28–35.

Tsurikova, A. P., and V. L. Tsurikov, 1971: On the concept of "salinity." *Oceanology*, **12**, 282–286.

Walker, E. R., and K. D. Chapman, 1973: Salinity-conductivity formulae compared. Rept. No. 73-5, Pacific Marine Science Environment Canada, 52 pp.

Weyl, P. K., 1964: On the change in electrical conductance of seawater with temperature. *Limnol. Oceanogr.*, **9**, 75–78.

Wooster, W. S., A. J. Lee and G. Dietrich, 1969: Redefinition of salinity. *Deep Sea Res.*, **16**, 321–322.

Zaburdaev, V. I., L. M. Dobruskina, E. F. Lyashenko and M. G. Poplavskaya, 1969: A method of determination of salinity from specific conductivity, temperature and pressure of seawater. *Oceanic Hydrol. Invest. Rept.*, No. 1(43), *Akad. Nauk Ukrainian S.S.R.*, Sevastopol, 5 pp.