The Extension of the Practical Salinity Scale 1978 to Low Salinities

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Abstract—**The Practical Salinity Scale (PSS) 1978 is defined only for salinities within the range 2–42. We have investigated the relationship between mass-determined salinity, electrical conductivity, and temperature for salinities between 0 and 2 with the aim of developing an extension to the Practical Salinity Scale 1978. The paper presents our data, on the basis of which the following correction is proposed to extend the validity of the equations defining the scale to the entire 0–42 range:**

$$S=\sum_{i=0}^{5}(a_i+b_if(t))R_t^{i/2}-\frac{a_0}{1+1.5x+x^2}-\frac{b_0f(t)}{1+y^{1/2}+y+y^{3/2}}$$

where

$$f(t)=\frac{(t-15)}{1+k(t-15)}$$

$$x=400R_t$$

$$y=100R_t$$

and the constants a_i, b_i, and k are defined by the Practical Salinity Scale 1978.

I. Introduction

The Practical Salinity Scale 1978 [1], [2] defines practical salinity S as a function of electrical conductivity, temperature t, and pressure p over specific ranges of applicability (S = 2 to 42, t = −2 to 35°C, p = 0 to 100 MPa). During the process of acquiring the data on which the Practical Salinity Scale is partly based, Dauphinee *et al.* [3] undertook a series of measurements at very low salinities at 15°C to study the relationship between electrical conductivity and salinity as the latter approached zero. Their data indicated that, although the data above S = 1 appeared to be extrapolating to S = 0.008–0.009 at an electrical conductivity of zero, the data at low salinities did, in fact, turn over sharply and approach S = 0 when the conductivity became zero. The Practical Salinity Scale 1978 equation that defines salinity includes a constant term and a term that is a function of temperature but independent of conductivity. In the limit of zero conductivity the equation reduces to the following form:

$$S(R_t=0)=a_0+b_0f(t) \tag{1}$$

where

$$a_0=0.008$$

$$b_0=0.0005$$

$$f(t)=\frac{(t-15)}{1+k(t-15)}$$

and

$$k=0.0162.$$

Fig. 1 depicts the behavior of the equation as a function of temperature. As has been pointed out previously [4], the constant term was included to better fit the low salinity end of the defined range (near S = 2).

We have undertaken the examination of the relationship between salinity, electrical conductivity, and temperature below S = 2 in an attempt to extend the validity of the Practical Salinity Scale to S = 0. Clearly, it would be highly undesirable to change the formulation of the equations defining the scale over their defined ranges of applicability. It is also obvious that the defined salinity should be zero when the conductivity is equal to the value for pure water [7]–[9]. However, the conductivity of pure water is less than 1×10^{-4} S/m over the temperature range of interest, whereas the conductivity of standard seawater (S = 35) at 15°C is approximately 4.2914 S/m [10], so little error will be introduced by adopting a correction which predicts S = 0 for zero conductivity. The paper presents the data in a form that shows the deviation of the measured values from those predicted by the Practical Salinity Scale (PSS). A model of the deviation is presented which, in the authors' opinion, fits the data well while being both simple in form and easily incorporated as a "correction" to the PSS. The form of the correction function is such that its influence above S = 2 is negligible; it can therefore be ignored above S = 2 or included in the calculation for all values of salinity.

Since the PSS is based on dilutions of standard seawater, the results are only strictly applicable to waters which have the major ions in the same proportions as standard seawater. Fortunately, this appears to hold throughout the world oceans. This constancy of composition does not apply, however, to coastal waters diluted by land drainage. This new work extends the range of the PSS to low salinities within the limitations of the definition of the scale. The utilization of the results to predict the composition or properties of naturally occurring low salinity waters is beyond the scope of the present work. Further experiments will be required to determine the degree to which natural waters deviate from the predictions of the PSS.

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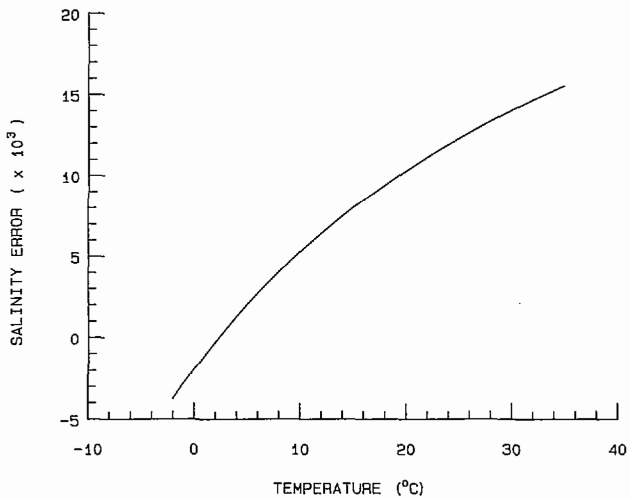

Fig. 1. The salinity at zero conductivity as predicted by the PSS 1978.

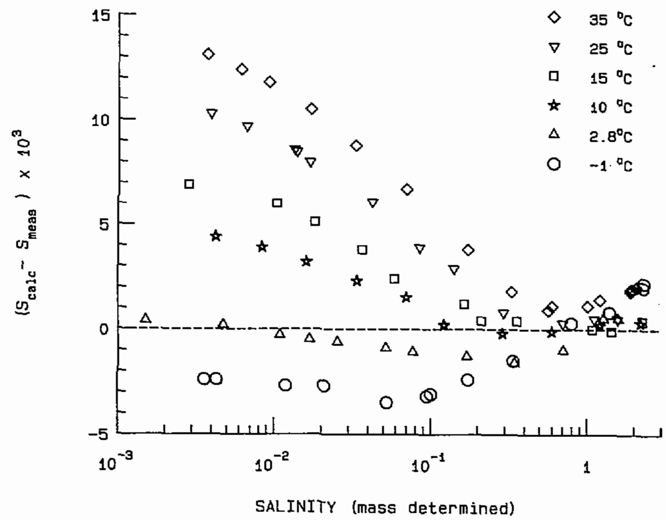

Fig. 2. The differences between the salinity predicted by the PSS and the mass determined salinity as a function of salinity for the six different temperatures indicated.

The following discussion will frequently refer to the quantity R_t. The PSS 1978 defines R_t as the ratio of the conductivity of seawater, at temperature t, to the conductivity of seawater of practical salinity $S = 35$ at the same temperature, both at a pressure of 1 standard atmosphere.

II. Experimental Method

The experimental apparatus is essentially the same as reported previously [3], [5]. The original cells were replaced by a new design with the sidearms extending completely out of the water, avoiding the requirement for a watertight submersible seal. We believe this design should offer reduced maintenance, increased reliability and, most important for low salinity measurements, greater resistance to electrical leakage.

The mass dilutions were performed using a Mettler H315 analytical balance. Appropriate corrections were made for the densities of seawater and pure water [1], and air [6]. At these very low salinities, the influence of buoyancy corrections is less than 1×10^{-4} in S. Therefore any uncertainties of the 1980 Equation of State used for the densities will truly be insignificant. The mass determined salinities are believed to be accurate to approximately $1 \times 10^{-4}\, S$. This is also consistent with our demonstrated repeatability. The mass dilutions always followed the sequence of first weighing the dry bottle, then the bottle with an appropriate amount of distilled water, and finally the bottle and the solution resulting from the addition of standard seawater (P79) to the distilled water.

The electrical conductivity of each sample was measured immediately following its preparation. The techniques involved in performing the conductivity measurements have been described previously [3], [5].

III. Presentation of the Data

The experimental data of Fig. 2 represent six sets corresponding to six temperatures from -1 to 35°C (-1, 2.8, 10, 15, 25, and 35°C), covering the range of validity of the PSS. The vertical axis is the salinity predicted by the PSS minus the mass determined salinity (calculated minus measured). The horizontal axis is salinity expressed on a logarithmic scale to better represent the nature of the deviations. The deviations from zero at $S = 2$ for the temperature extremes (-1, 35°C) are not indicative of errors in the present data, but merely reflect the limitations of the form of the equations used to fit the original data for $S > 2$ [4]. The values of salinity measured in the present experiments agree closely with the previously measured values near $S = 2$. All of the data sets appear to be extrapolating to the values predicted by (1) at low salinity, indicating that the true salinity does indeed go to zero at zero conductivity.

IV. Fitting the Deviations

The nature of Fig. 2 suggests that the deviations between the calculated and measured salinities are indeed systematic. We have taken an approach to modeling the deviation function similar to that used in fitting the data to define the PSS. First, a function was chosen to fit the deviation at 15°C. Some inspired guessing led to the form

$$S_{calc} = S_{\text{PSS}} - \frac{a_0}{1+1.5x+x^2} \tag{2}$$

where

$$S_{\text{PSS}} = \sum_{i=0}^{5} (a_i + b_i f(t)) R_t^{i/2}$$

and

$$x = 400 R_t.$$

Fig. 3 represents the result of applying this equation to the data of Fig. 2. The remaining deviation represents a correction to the temperature-dependent part of the equation. As with the 15°C term, the weighting of the correction is determined by the constant term in the original equation defining the scale. The final equation is

$$S_{calc} = S_{\text{PSS}} - \frac{a_0}{1+1.5x+x^2} - \frac{b_0 f(t)}{1+y^{1/2}+y+y^{3/2}} \tag{3}$$

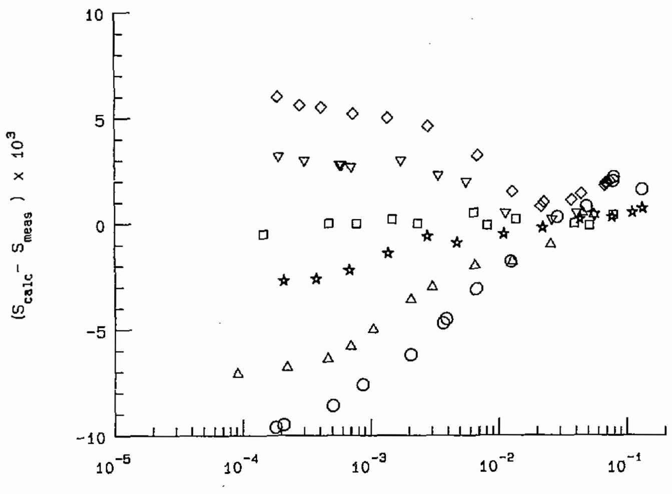

Fig. 3. The residual salinity differences after applying (2) to the data of Fig. 2. This represents the fit to the 15°C data. The horizontal axis is the conductivity ratio R_t.

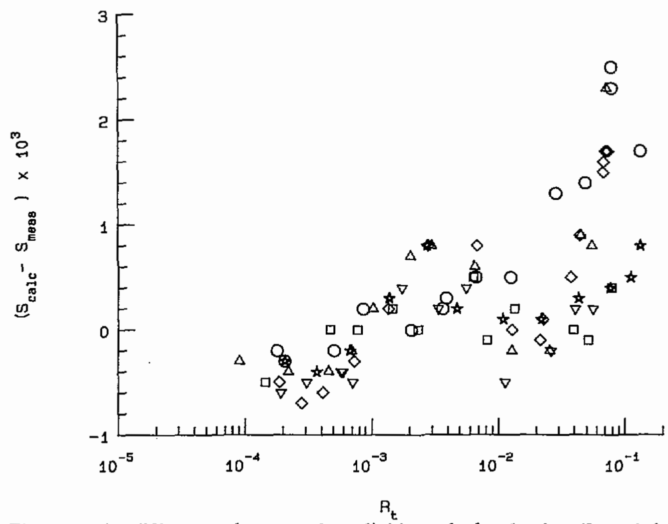

Fig. 4. The differences between the salinities calculated using (3) and the mass determined salinities. This represents the effectiveness of the proposed low salinity extension to the PSS.

where $y = 100\ R_t$. The constants a_0 and b_0 are the same constants defined by the PSS.

Although these correction terms are the result of empirical fits to the data, it is clear that they model the data well, as Fig. 4 shows. The residual errors are less than ± 0.001 over the range of data collected, except for the deviations near $S = 2$ at the extremes of temperature where the PSS is already recognized as failing to fit the data, as mentioned previously. There appears indeed to be a trend in the data which (3) has not removed since the residual deviations for the data sets at a particular value of R_t exhibit a scatter of considerably less than ± 0.001 in practical salinity.

V. Conclusion

The relationship between salinity, electrical conductivity, and temperature has been investigated for the range $S = 0$ to 2 with the aim of extending the validity of the PSS to this region. The final equation defining salinity may be written as

$$S=\sum_{i=0}^{5} (a_i+b_i f(t))R_t^{i/2}-\frac{a_0}{1+1.5x+x^2}-\frac{b_0 f(t)}{1+y^{1/2}+y+y^{3/2}} \tag{4}$$

where

$$f(t)=\frac{(t-15)}{1+k(t-15)}$$

$$x=400R_t$$

$$y=100R_t$$

and the constants a_i, b_i, and k are defined by the Practical Salinity Scale 1978 [1], [2].

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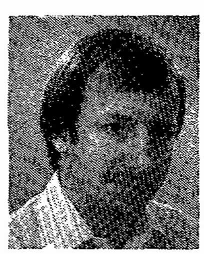

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Dr. Dauphinee was the winner of the 1978 Morris E. Leeds Award (IEEE) for "the application of physical principles to instrumentation and measurement" and has a number of published papers and patents in the instrumentation field. He is a member of the IEEE Council on Oceanic Engineering, and is an Associate Editor of the IEEE Journal of Oceanic Engineering. On the international scene, he is an Advisor to UNESCO-SCOR-ICES-IAPSO Joint Panel on Oceanographic Tables and Standards and a member of SCOR WG 51 on Evaluation of CTD data.

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