Determination of dissolved oxygen in sea water by Winkler titration

Andrew G. Dickson
Scripps Institution of Oceanography
9500 Gilman Drive
La Jolla, CA 92093-0902, USA

1.   Scope and field of application

This procedure describes a manual method based on the Winkler procedure for the determination of dissolved oxygen in sea water (Footnote 1).The method is suitable for the measurement of oceanic levels of oxygen (0–400 $\mu mol \cdot kg^{-1}$: Footnote 2) in uncontaminated sea water. (This method is unsuitable in sea water containing hydrogen sulfide.)
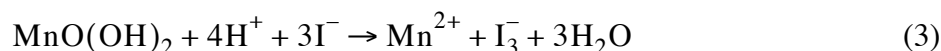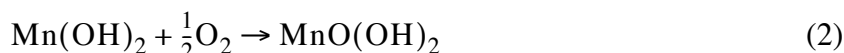
2.   Definition

The dissolved oxygen content of sea water is defined as the number of moles of dioxygen gas (O_2) per kilogram of sea water.

3.   Principle

The basis of the Winkler procedure is that the oxygen in a sea water sample is made to oxidize iodide ion to iodine quantitatively (in the presence of an alkaline solution of manganese (II) ion); and the amount of iodine generated in this fashion is determined by titration with a standard thiosulfate solution. The end-point is located using starch as a visual indicator for the presence of iodine. The amount of oxygen present in the original sample can then be computed from the titer.

The relevant chemical reactions occurring in the solution are:

$$Mn^{2+} + 2OH^- \rightarrow Mn(OH)_2 \tag{1}$$

$$Mn(OH)_2 + \tfrac{1}{2}O_2 \rightarrow MnO(OH)_2 \tag{2}$$

$$MnO(OH)_2 + 4H^+ + 3I^- \rightarrow Mn^{2+} + I_3^- + 3H_2O \tag{3}$$

$$I_3^- + 2S_2O_3^{2-} \rightarrow 3I^- + S_4O_6^{2-} \tag{4}$$

---

[1]   A number of investigators have automated this procedure (using either changes in the absorption due to the triiodide ion to detect the endpoint—see e.g. Williams & Jenkinson, 1982—or an amperometric technique—see e.g. Culberson & Huang, 1987). Such approaches are potentially more convenient than the manual method detailed here.

[2]   Significantly higher levels of O_2—up to 535 $\mu mol \cdot kg^{-1}$—have been observed in cold waters with high plankton blooms. See Note 11 for information on how to adapt this technique to handle such levels.

i.e. 1 mol of O_2 reacts with 4 mol of $S_4O_6^{2-}$. The thiosulfate solution is standardized against a gravimetrically prepared solution of potassium iodate which is in turn used to oxidize iodide ion to iodine:

$$IO_3^- + 8I^- + 6H^+ \rightarrow 3I_3^- + 3H_2O \tag{5}$$

The experimental measurement using this technique thus essentially determines the ratio between the concentration of iodate in a standard solution and the concentration of oxygen in the sample using thiosulfate as a transfer standard.

4.   Apparatus

4.1   Sampling

4.1.1   Sample flasks: Erlenmeyer flasks of 125 cm³ nominal capacity ("iodine" flasks) with ground glass stoppers (Footnote 3), calibrated in accordance with SOP 13 (Footnote 4).

4.1.2   Pickling reagent dispensers: two dispensers capable of dispensing 1 cm³ aliquots of the pickling reagents (Footnote 5).

4.1.3   Flexible plastic drawing tube (Footnote 6), long enough to reach from the drain on the water sampler to the bottom of the sample bottle and with an internal diameter chosen to fit the sample bottle spigot (Footnote 7).

4.1.4   Thermometers: one thermometer is used to measure the water temperature at sampling to within 0.5 °C (Footnote 8), another is used to monitor the temperature of the laboratory—also to within 0.5 °C.

4.2   Titration apparatus

4.2.1   Titration box: an open-front box containing the titration apparatus. The walls of the box are painted white and adequate illumination is provided to enable the operator to see clearly the color change associated with the end point.

4.2.2   Burette: a piston burette with a 1 cm³ capacity and an "anti-diffusion" tip.

4.2.3   Dispenser: capable of dispensing 1 cm³ 5 M H_2SO_4.

4.2.4   Precise dispenser: capable of dispensing 1 cm³ KIO_3 solution (used in the blank determination). The volume should be calibrated in accordance with SOP 12 (Note 4).

4.2.5   Precise dispenser of 10 cm³ capacity (Footnote 9), used to dispense the standard KIO_3 solution. The volume should be calibrated in accordance with SOP 12 (Note 4).

---

[3]   It is essential that each individual flask/stopper pair be marked to identify them and that they be kept together in subsequent use.

[4]   The Standard Operating Procedures (SOPs) cited in this procedure for the volumetric calibration of glassware *etc*. refer to procedures detailed in DOE (1994).

[5]   Confirm that the volume dispensed is accurate to ± 0.02 cm³ by dispensing 10 aliquots into a measuring cylinder.

[6]   Tygon® tubing is typically used for this purpose, however silicone rubber tubing can also be used.

[7]   The drawing tube should be pre-treated by soaking in clean sea water for at least one day. This minimizes the amount of bubble formation in the tube when drawing a sample.

[8]   It is convenient to incorporate a thermometer sensor into the drawing tube so that the water flows past the sensor on its way into the sampling bottle.

[9]   For example, a Knudsen style pipette.

4.2.6   Magnetic stirrer and a number of stirrer bars.

5.   Reagents

5.1   Manganous chloride solution (3 M): Dissolve 600g of $MnCl_2 \cdot 4H_2O$ in deionized water, then dilute the solution with deionized water to a final volume of 1 dm^3. Finally, filter the solution through a coarse filter paper.

5.2   Sodium hydroxide (8 M) / sodium iodide solution (4 M): Dissolve 320 g NaOH in about 500 cm^3 of deionized water, allow to cool, then add 600 g NaI and dilute with deionized water to a final volume of 1 dm^3 (Footnote 10). Finally, filter the solution through a coarse filter paper.

5.3   Sulfuric acid solution (5 M): Slowly add 280 cm^3 of concentrated H_2SO_4 to 770 cm^3 of deionized water. After cooling the final volume should be 1 dm^3.

5.4   Starch / glycerol indicator solution: Make a paste of 30 g of soluble starch in 100 cm^3 glycerol ($HOCH_2CHOHCH_2OH$), stir into about 900 cm^3 glycerol. Heat the solution until it starts to boil. Cool.

5.5   Sodium thiosulfate (0.2 M): Dissolve 50 g $Na_2S_2O_3 \cdot 5H_2O$ in deionized water, then dilute the solution with deionized water to a final volume of 1 dm^3 (Footnote 11).

5.6   Potassium iodate (0.0023 M): Dry high purity KIO_3 in an oven at 170 °C. Weigh out accurately about 0.5 g of KIO_3, dissolve it in deionized water and dilute the solution to a final volume of 1 dm^3 in a calibrated volumetric flask (see SOP 13—Note 4). Note the temperature of the solution.

6.   Sampling

6.1   Introduction

Collection of water at sea, from the Niskin bottle or other sampler, must be done soon after opening the sampler and before much other water has been removed from it (Footnote 12). This is necessary to minimize exchange of O_2 with the head space in the sampler.

---

[10]   If sampling in an area of low oxygen (<5 $\mu mol \cdot kg^{-1}$) with known high nitrite (>5 $\mu mol \cdot kg^{-1}$), add 2 g of sodium azide (NaN_3) to the solution before diluting to the final volume (Note: NaN_3 is considered an extremely hazardous substance and should be handled appropriately.

[11]   The concentrations for the $Na_2S_2O_3$ and KIO_3 reagents used here are higher than were originally recommended by Carpenter (1965). This allows most oceanic O_2 concentrations to be analyzed. If the highest concentrations of O_2 expected are <280 $\mu mol \cdot kg^{-1}$, the original concentrations (0.14 M $Na_2S_2O_3$ and 0.0017 M KIO_3) are appropriate. If concentrations

In such cases, it may be appropriate to adjust the reagent concentrations (if a number of samples with high oxygen concentrations are expected), or simply to refill the burette and continue with the titration (for individual samples).

[12]   It is difficult to collect an O_2 sample without atmospheric contamination from a Niskin sampler with a volume of less than 2 dm^3.

6.2   Sampling procedure

6.2.1   Confirm that the flask and stopper pair match.

6.2.2   Rinse the drawing tube—Run a small volume of sample water through the drawing tube to remove air.

6.2.3   Rinse the sample bottle—If the bottle is not already clean and dry, it is rinsed twice by swirling with 30 cm^3 of fresh sample so as to remove any traces of reagents from a previous analysis (Footnote 13).

6.2.4   Fill the sample bottle—The bottle is filled smoothly, minimizing turbulence and avoiding aeration, from the bottom using a Tygon® tube which extends from the Niskin drain to the bottom of the glass sample bottle. The water is overflowed by three flask volumes (Footnote 14).

6.2.5   Note sampling temperature—Record the temperature of the water being sampled while the sample is overflowing the flask (Footnote 15).

6.2.6   Add pickling reagents —The $MnCl_2$ and the NaOH/NaI reagents should be added immediately after the sample is drawn (Footnote 16). The dispenser tips should be submerged at least 1 cm below the neck of the sample flasks before dispensing (Footnote 17).

6.2.7   Close the bottle and mix—The stopper is then inserted carefully into the flask, displacing the excess sea water but without trapping bubbles. The flask is then shaken vigorously to mix the contents thoroughly and to disperse the precipitate finely throughout.

6.2.8   Shake the bottle a second time—After the precipitate has settled at least halfway down the bottle (about 20 minutes), shake the bottle vigorously to disperse the precipitate.

6.2.9   Storage—Flasks containing pickled samples should be stored in a cool, dark, location until they are titrated.

7.   Titration procedures

7.1   Determination of the blank (*Footnote 18*)

7.1.1   Place 50 cm^3 deionized water in a clean flask and add a magnetic stirring bar.

7.1.2   Add 1 cm^3 of standard potassium iodate solution using the calibrated dispenser.

7.1.3   Add 1 cm^3 of 5 M H_2SO_4 and stir thoroughly.

7.1.4   Add 1 cm^3 of the NaOH / NaI reagent and stir thoroughly.

---

[13]   This rinse water will leave a film that is approximately in equilibrium with atmospheric oxygen levels. For uncontaminated measurement of low oxygen levels it is best to use clean, dry, bottles.

[14]   The amount of overflow water can be estimated by measuring how long it takes to fill a sample flask and allowing the water to overflow for a period of 3 times that.

[15]   In subsequent calculations, it is assumed that the sample flask has also reached this temperature.

[16]   Keep these reagents at about. 25 °C as long as possible. The oxygen solubility is known at this temperature. If they are cooled, *e.g.* by being outside in cold weather, they will absorb additional oxygen from the atmosphere.

[17]   This reduces contamination with atmospheric oxygen and ensures that the precipitate does not form in the excess sea water above the neck of the flask.

[18]   A duplicate determination should always be done.

7.1.5   Add 1 cm^3 of the MnCl$_2$ reagent and stir thoroughly.

7.1.6   Fill flask to the neck with deionized water.

7.1.7   Titrate the liberated iodine with thiosulfate immediately to minimize loss of iodine by volatilization. Add thiosulfate, titrating the solution until it is a light straw color.

7.1.8   Add 0.3 cm^3 starch solution. This should give the sample a deep blue color.

7.1.9   Titrate precisely to the end-point—a clear solution—with Na$_2$S$_2$O$_3$ solution.

7.1.10 Add a further 1 cm^3 of standard iodate solution.

7.1.11 Titrate the liberated iodine.

7.2   *Standardization of sodium thiosulfate titrant (Note 18)*

7.2.1   Place 50 cm^3 deionized water in a clean flask and add a magnetic stirring bar.

7.2.2   Add 10 cm^3 of standard potassium iodate solution using the calibrated dispenser.

7.2.3   Add 1 cm^3 of 5 M H$_2$SO$_4$ and stir thoroughly.

7.2.4   Add 1 cm^3 of the NaOH / NaI reagent and stir thoroughly.

7.2.5   Add 1 cm^3 of the MnCl$_2$ reagent and stir thoroughly.

7.2.6   Fill flask to the neck with deionized water.

7.2.7   Titrate the liberated iodine with thiosulfate immediately to minimize loss of iodine by volatilization. Add thiosulfate rapidly at first, titrating the solution until it is a light straw color.

7.2.8   Add 0.3 cm^3 starch solution. This should give the sample a deep blue color.

7.2.9   Continue titrating to the end-point—a clear solution.

7.2.10 Record the room temperature.

7.3   *Titration of a sample*

7.3.1   Remove the ground-glass stopper.

7.3.2   Add 1 cm^3 of 5 M H$_2$SO$_4$.

7.3.3   Add a magnetic stirrer bar to the solution and begin stirring.

7.3.4   After most of the precipitate has dissolved, titrate the liberated iodine with thiosulfate immediately to minimize loss of iodine by volatilization. Add the thiosulfate rapidly at first, titrating the solution until it is a light straw color.

7.3.5   Add 0.3 cm^3 starch solution. This should give the sample a deep blue color.

7.3.6   Continue titrating to the endpoint—a clear solution (Footnote 19).

7.3.7   Record the room temperature.

7.4   *Clean flasks*

The flasks should be rinsed thoroughly with fresh water to remove traces of the reagents prior to their next use.

---

[19]   If the endpoint is overtitrated, the sample can be "rescued" by the addition of 1.000 cm^3 of KIO$_3$ and then titrating to a new endpoint. It is then necessary to correct the final titre by V_1 to obtain the titre appropriate to the original sample.

8.   Calculation and expression of results

8.1   Titration blank

The "blank" results from the presence of redox species apart from oxygen in the reagents which can behave equivalently to oxygen in the analysis. It is given by the expression

$$V_{blank} = V_2 - V_1 \,, \tag{6}$$

where V_1 and V_2 are the volumes of $Na_2S_2O_3$ used to titrate the first and second aliquots of KIO_3 respectively (Footnote 20).

8.2   Concentration of standard KIO$_3$ solution

The concentration of the standard KIO_3 solution—corrected to 20 °C—is given by the expression:

$$M(KIO_3, 20\ °C) = \frac{m(KIO_3)/(213.995\ \text{g·mol}^{-1})}{V_S} \times \frac{\rho_w(20\ °C)}{\rho_w(t_L)} \,; \tag{7}$$

where $m(KIO_3)$ is the mass of KIO_3 that was made up with deionized water to a total volume, V_S (Footnote 21);

$$V_S = V_S(20\ °C)\{1 + \alpha_V(t_L - 20\ °C)\} \quad . \tag{8}$$

213.995 g·mol^{-1} is the molar mass of KIO_3; $\rho_w(t_L)$ is the density of pure water at the laboratory temperature when the solution was prepared (t_L) — see Appendix (A.1).

8.3   Molarity of Na$_2$S$_2$O$_3$ titrant

The molarity of the titrant can be calculated from the expression:

$$M(Na_2S_2O_3) = \frac{6 \cdot V(KIO_3) \cdot M(KIO_3)}{V_{std} - V_{blank}} \,, \tag{9}$$

where V_{std} is the average volume of titrant used to titrate $V(KIO_3)$ of standard KIO_3 solution. This expression is only exact if the measurements are performed at 20 °C: however, if the titrant is at approximately the same temperature as the KIO_3 standard solution, errors in volume measurement will tend to cancel. Then, if the value used for $M(KIO_3)$ refers to 20 °C, so will $M(Na_2S_2O_3)$.

---

[20]   Some investigators also make a correction for the presence of other redox species apart from oxygen in the sample which can behave equivalently to oxygen in the analysis. These are typically estimated by measuring the "blank" directly in an aliquot of the sea water. This is not done here.

[21]   The volume of the flask is corrected to the actual temperature measured when making up the solution (see SOP 13—Note 4).

8.4 Oxygen in a sea water sample

Oxygen dissolved in the pickling reagents introduces oxygen into the sample prior to the analysis. The total number of moles of O_2 reacted (sample + reagents) can be calculated from the expression

$$n(O_2) = \frac{1.5 \cdot (V - V_{blank}) \cdot V(KIO_3) \cdot M(KIO_3)}{V_{std} - V_{blank}} \ , \tag{10}$$

where V is the volume of titrant needed to titrate the sample. The factor 1.5 results from the fact that 1 mol of O_2 can be considered to react with 4 mol of $Na_2S_2O_3$ and 1 mol of KIO_3 reacts with 6 mol of $Na_2S_2O_3$ (see § 3)

It is assumed in writing (10) that the titrant had approximately the same temperature when titrating both the standards and the samples. It is, however, necessary to use values for $V(KIO_3)$ and for $M(KIO_3)$ appropriate to the laboratory temperature (t_L). $V(KIO_3)$ can be estimated using the expression:

$$V(KIO_3) = V(\text{pipette, 20 °C})\{1 + \alpha_V(t_L - 20 \text{ °C})\} \tag{11}$$

and

$$M(KIO_3) \approx M(KIO_3, 20 \text{ °C})\frac{\rho_w(t_L)}{\rho_w(20 \text{ °C})} \tag{12}$$

The concentration of oxygen in sea water is then given by

$$C(O_2) = \frac{n(O_2) - 7.6 \times 10^{-8} \text{ mol}}{m(\text{sample})} \ , \tag{13}$$

where $m(\text{sample})$ is the mass of sea water that was pickled, and the amount of oxygen introduced to the sample in 1 cm^3 $MnCl_2$ and 1 cm^3 NaOH/NaI reagent at about 25 °C has been estimated at 7.6×10^{-8} mol;

$$m(\text{sample}) = (V(O_2\text{-flask}) - 2 \text{ cm}^3) \cdot \rho_{sw}(S, t) \ . \tag{14}$$

The volume of the oxygen flask, $V(O_2\text{–flask})$ is that appropriate to the temperature at which the sample was pickled (t);

$$V(O_2\text{-flask}) = V(O_2\text{-flask, 20 °C})\{1 + \alpha_V(t - 20 \text{ °C})\} \quad ; \tag{15}$$

the density of sea water used—$\rho_{sw}(S, t)$; see Appendix (A.2)—is also that appropriate to the temperature at which the oxygen sample was pickled.

8.5   *Example calculations (Footnote 22)*

8.5.1   *Titration blank*

$V_1 = 0.0700$ cm^3;

$V_2 = 0.0750$ cm^3;

$V_{blank} = 0.0050$ cm^3 — Equation (6).

8.5.2   *Concentration of standard KIO$_3$ solution*

m (KIO_3) = 0.5000 g;

$t_L = 18.0$ °C (laboratory temperature);

$V_S(20°C) = 1.0001$ dm^3;

$V_S(18°C) = 1.00008$ dm^3 — Equation (8);

$\rho_W(18°C) = 0.99859$ g·cm^{-3} — Equation *(A.1)*;

$\rho_W(20°C) = 0.99820$ g·cm^{-3} — Equation (A.1);

M (KIO_3, 20 °C) = 0.0023354 mol·dm^{-3} — Equation (7).

8.5.3   *Molarity of Na$_2$S$_2$O$_3$ titrant*

(Assumes that the $Na_2S_2O_3$ titrant is at approximately the same temperature as the KIO_3.)

$V_{std} = 0.7000$ cm^3;

$V(KIO_3) = 10.0000$ cm^3;

$M(Na_2S_2O_3) = 0.20162$ mol·dm^{-3} — Equation (9).

8.5.4   *Oxygen in a sea water sample*

$S = 35.0$;

$t = 0.0$ °C (sampling temperature);

$t_L = 23.0$ °C (laboratory temperature);

$\rho_W(23°C) = 0.99753$ g·cm^{-3} (Equation A.1);

V (KIO_3, 23°C) = 10.0003 cm^3 — Equation (11);

M (KIO_3, 23°C) = 0.0023338 mol·dm^{-3} — Equation (12);

$V = 0.9500$ cm^3;

n (O_2) = 47.602 µmol — Equation (10);

V (O_2-flask, 20 °C) = 125.000 cm^3;

V (O_2-flask, 0 °C) = 124.976 cm^3;

$\rho_{SW}(35, 0°C) = 1.02811$ g·cm^{-3} — Equation (A.2);

m(sample) = 0.12643 kg — Equation (14);

C (O_2) = 375.90 µmol·kg^{-1} — Equation (13).

---

[22]   Note, extra significant figures are provided to assist in checking calculations.

9.   Quality assurance

Some duplicate sampling is recommended to assess the quality of the sampling procedures; both from the same sampler (*e.g.* Niskin bottle) and ideally from two samplers tripped together at the same depth.

The control limits outlined below are necessary to ensure that the accuracy and precision of the data are adequate for the purposes of the WOCE Hydrographic Program. The initial targets specified for this are: a maximum within cruise precision (1 std. dev.) of 0.5 $\mu mol \cdot kg^{-1}$ and an overall, between cruise (and between laboratory), range of bias of less than 2.0 $\mu mol \cdot kg^{-1}$. Results from an intercalibration exercise including an implementation of this method indicate that these targets are attainable.

Preliminary results should be calculated immediately and the control charts outlined below should be updated as soon as possible. A logbook should be maintained detailing all the analyses carried out and describing any adjustments made to the analytical system. The following goals are recommended:

9.0.1   Reagent and titration blank

This should be less than 0.01 cm^3, otherwise it is indicative of problems. A property control chart should be kept of this parameter (SOP 22— Note 4).

9.0.2   Precision of titration of standard KIO_3 solution

A duplicate titration of the standard KIO_3 solution should be made for every set of samples. The difference in volume of $Na_2S_2O_3$ used for each pair of analyses should be plotted on a range control chart (SOP 22— Note 4). This difference should typically be less than 0.0020 cm^3.

9.0.3   Molarity of $Na_2S_2O_3$ solution

The molarity of the $Na_2S_2O_3$ titrant (20 °C) should be calculated for each standardization and the results should be plotted on a property control chart (SOP 22— Note 4). This will show any gradual change of the $Na_2S_2O_3$ solution with time and will allow an early identification of any problems.

9.0.4   Precision of oxygen analysis

A duplicate sample should be taken and titrated approximately every 10–15 analyses. The difference in oxygen concentration obtained for each pair of analyses should be plotted on a range control chart (SOP 22— Note 4).

References

Bigg P. H. (1967) Density of water in SI units over the range 0–40 °C. *British Journal of Applied Physics* **18**, 521–525.

Carpenter J. H. (1965) The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. *Limnology and Oceanography* **10**, 141–143.

Commission on Atomic Weights and Isotopic Abundances (1988) Atomic weights of the elements 1987. *Pure & Applied Chemistry* **60**, 841–854.

Craig H. (1961) Standards for reporting concentrations of deuterium and oxygen-18 in natural waters. *Science* **133**, 1833–1834.

Culberson C. H. & S. Huang (1987) Automated amperometric oxygen titration. *Deep-Sea Research* **34**, 875–880.

Culberson C. H. (1991) Dissolved oxygen. *In* WOCE Operations Manual. Volume 3: The Observational Program. Section 3.1: WOCE Hydrographic Program. Part 3.1.3: WHP Operations and Methods. WHP Office Report WHPO 91-1 / WOCE Report No. 68/91.

Culberson C. H., G. Knapp, M. C. Stalcup, R. T. Williams & F. Zemlyak (1991) A comparison of methods for the determination of dissolved oxygen in sea water. WHP Office Report WHPO-91-2.

DOE (1994) *Handbook of methods for the analysis of the various parameters of the carbon dioxide system in sea water; version 2*. A. G. Dickson & C. Goyet (eds.), ORNL/CDIAC-74. (This document is available on request from the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN37831-6335, USA)

Jones F. E. & G. L. Harris (1992) ITS$_{90}$ density of water formulation for volumetric standards calibration. *Journal of Research of the National Institute of Standards and Technology* **97**, 335–340.

Millero F. J. & A. Poisson (1981) International one-atmosphere equation of state for sea water. *Deep-Sea Research* **28**, 625–629.

Murray C. N., J. P. Riley & T. R. S. Wilson (1968) The solubility of oxygen in Winkler reagents used for the determination of dissolved oxygen. *Deep-Sea Research* **15**, 237–238.

Williams P. J. LeB. & N. W. Jenkinson (1982) A transportable microprocessor-controlled precise Winkler titration suitable for field station and shipboard use. *Limnology & Oceanography* **27**, 576–584.

Appendix A

Density of air-saturated water

The density of air-saturated water in the temperature range 5 to 40 °C—*i.e.* avoiding the temperature of maximum density—is given by the expression (Jones & Harris, 1992):

$$\rho_W / (\text{kg·m}^{-3}) = 999.84847 + 6.337563 \times 10^{-2} \, (t/°C)$$
$$- \, 8.523829 \times 10^{-3} \, (t/°C)^2 + 6.943248 \times 10^{-5} \, (t/°C)^3$$
$$- \, 3.821216 \times 10^{-7} \, (t/°C)^4, \tag{A.1}$$

where t is the temperature on ITS$_{90}$ (Footnote 23).

At 25 °C, $\rho_W = 997.041 \text{ kg·m}^{-3} = 0.997041 \text{ g·cm}^{-3}$.

Density of sea water

The density of sea water in the temperature range 0 to 40 °C (IPTS$_{68}$—see Note 23) and the salinity range 0 to 42 is given by the expression (Millero & Poisson, 1981):

$$\rho_{SW} / (\text{kg·m}^{-3}) = \rho_{SMOW} / (\text{kg·m}^{-3}) + A\,S + B\,S^{1.5} + C\,S^2 \tag{A.2}$$

where (Footnote 24)

$$\rho_{SMOW} / (\text{kg·m}^{-3}) = 999.842594 + 6.793952 \times 10^{-2} \, (t/°C)$$
$$- \, 9.095290 \times 10^{-3} \, (t/°C)^2 + 1.001685 \times 10^{-4} \, (t/°C)^3$$
$$- \, 1.120083 \times 10^{-6} \, (t/°C)^4 + 6.536332 \times 10^{-9} \, (t/°C)^5, \tag{A.3}$$

$$A = 8.24493 \times 10^{-1} - 4.0899 \times 10^{-3} \, (t/°C)$$
$$+ \, 7.6438 \times 10^{-5} \, (t/°C)^2 - 8.2467 \times 10^{-7} \, (t/°C)^3$$
$$+ \, 5.3875 \times 10^{-9} \, (t/°C)^4 , \tag{A.4}$$
$$B = -5.72466 \times 10^{-3} + 1.0227 \times 10^{-4} \, (t/°C)$$
$$- \, 1.6546 \times 10^{-6} \, (t/°C)^2 , \tag{A.5}$$
$$C = 4.8314 \times 10^{-4}; \tag{A.6}$$

t is on IPTS$_{68}$ and S is the salinity.

At 25 °C (IPTS$_{68}$) and $S = 35$, $\rho_{SW} = 1023.343 \text{ kg·m}^{-3}$.

---

[23] The International Practical Temperature Scale of 1968 (IPTS$_{68}$) has recently been superseded by the International Temperature Scale of 1990 (ITS$_{90}$). A simple equation can be used to relate the two over the oceanographic temperature range 0 to 40 °C (Jones & Harris, 1992):

$$t_{90} / °C = 0.0002 + 0.99975 \, t_{68} / °C.$$

[24] SMOW — Standard Mean Ocean Water (Craig, 1961)—is pure water with a specified isotopic composition and free of dissolved gases.