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The measurement of pH in saline and hypersaline media at sub-zero temperatures: Characterization of Tris buffers

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Abstract

The pH on the total proton scale of the Tris-HCl buffer system (pHTris) was characterized rigorously with the electrochemical Harned cell in salinity (S) 35 synthetic seawater and S = 45–100 synthetic seawater-derived brines at 25 and 0 °C, as well as at the freezing point of the synthetic solutions (−1.93 °C at S = 35 to −6 °C at S = 100). The electrochemical characterization of the common equimolal Tris buffer [RTris = mTris/mTris = 1.0, with mTris = mTris-H+] = 0.04 mol kgH2O−1 = molality of the conjugate acid-base pair of 2-amino-2-hydroxymethyl-1,3-propanediol (Tris)] yielded pHTris values which increased with increasing salinity and decreasing temperature. The electrochemical characterization of a non-equimolal Tris buffer variant (RTris = 0.5, with mTris = 0.02 mol kgH2O−1 and mTris-H+] = 0.04 mol kgH2O−1) yielded pHTris values that were consistently less alkaline by 0.3 pH unit than those of the equimolal Tris buffer. This is in agreement with the values derived from the stoichiometric equilibrium of the Tris-H+ dissociation reaction, described by the Henderson – Hasselbalch equation, pHTris = pKTris + log RTris, with pKTris = stoichiometric equilibrium dissociation constant of Tris-H+, equivalent to equilibrium pHTris. This consistency allows reliable use of other RTris variants of the Tris-HCl buffer system within the experimental conditions reported here. The results of this study will facilitate the pH measurement in saline and hypersaline systems at below-zero temperatures, such as sea ice brines.

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1. Introduction

High latitude oceans contribute disproportionately to the CO2 uptake from the atmosphere (Bates and Mathis, 2009; Takahashi et al., 2002), but these estimates are based on data generated by sampling ice-free parts of the polar oceans. A complete picture of the polar CO2 budget must include the role of the seasonal and perennial sea ice in CO2 cycling and air-sea exchange in these regions. Recent research has demonstrated that brine pockets in sea ice are sites of physical and biogeochemical processing that render sea ice an environment of active carbon cycling (Arrigo et al., 1997; Dieckmann et al., 2008; Gleitz et al., 1995; Miller et al., 2011a, 2011b; Munro et al., 2010; Papadimitriou et al., 2012; Rysgaard et al., 2011; Rysgaard et al., 2007). Processes, such as primary and secondary production (Arrigo et al., 1997; Deming, 2010), mineral authigenesis, including CaCO3 in the form of ikaite (Dieckmann et al., 2010; Dieckmann et al., 2008; Rysgaard et al., 2013), gas exchange (Miller et al., 2011a, 2011b; Papadimitriou et al., 2012; Papadimitriou et al., 2004), and brine drainage (Notz and Worster, 2009) have dynamic seasonal cycles in sea ice and affect the carbonate system at the ocean-air interface in high latitudes (Bates and Mathis, 2009; Bates et al., 2006; Chierici and Fransson, 2009; Dieckmann et al., 2008; Fischer et al., 2013; Miller et al., 2011b; Papadimitriou et al., 2014; Papadimitriou et al., 2013; Rysgaard et al., 2012; Takahashi et al., 2002; Yamamoto–Kawai et al., 2011; Yamamoto–Kawai et al., 2009).

However, in comparison with the current advancement of our knowledge on ice-free waters of the high latitude oceans, the study of the carbonate system in sea ice has been patchy, not least because of logistical and physical-chemical complexities (Miller et al., 2015).

Sea ice is a porous medium of mostly pure ice with a small percentage by volume of brine and gas pockets (Cox and Weeks, 1983). The chemical composition of the liquid and gas phases of sea ice results from the physical-chemical changes attendant on seawater freezing, its dissolved salt and gas expulsion from the pure ice matrix, and their entrainment and physical concentration in pockets within (Cox and Weeks, 1983). Thus, sea ice brines exhibit a much wider range of salinity...
(S) and temperature (t) within short temporal and spatial scales than the underlying and ice-free oceanic waters. The temperature of sea ice ranges from the freezing point of seawater at the ice-water interface ($t_{w} = -1.93 \, ^\circ C$ at 1 atm total pressure and $S = 35$; UNESCO (1983)]) to temperatures as low as $-16 \, ^\circ C$, or even lower during winter, in the coldest upper parts of ice floes in contact with the atmosphere (Miller et al., 2011a, 2011b) accommodating hypersaline ($S \gg 35$) brines of an equivalent freezing point. For example, at $-6 \, ^\circ C$, about 66% of the water is present as ice and the residual brine has a salinity of 100. The temperature range where in situ investigation of the carbonate system in sea ice would be most beneficial is between the freezing point of seawater and the temperature at which the sea ice becomes impermeable to liquid transport and material exchange with the underlying ocean. This occurs when the brine volume becomes <5%, which occurs at $-5 \, ^\circ C$ when bulk sea ice $S = 5$ (Golden et al., 1998).

For the investigation of the carbonate system under such S–t conditions as found in sea ice, total alkalinity (TA), total dissolved inorganic carbon (DIC), and dissolved CO$_2$ (as gas fugacity, fCO$_2$) measurements are possible using current methodologies and instrumentation (Miller et al., 2015) but not the measurement of pH, which is only possible thus far at above-zero temperatures and salinities up to 40. An estimate of the pH at the sub-zero temperatures and high salinities of sea ice brines can be computed from the solution of the thermodynamic model that describes the oceanic carbonate system using measurements of TA and DIC as input parameters (Brown et al., 2014; Delille et al., 2007; Gleitz et al., 1995; Papadimitriou et al., 2007). This requires knowledge of the dissociation constants of carboxylic and boric acids at the salinity and temperature ranges of sea ice. Empirical data for these constants, however, do not exist for $t < 0 \, ^\circ C$ and $S > 35$ in natural solutions (Dickson, 1990a; Millero et al., 2006). The required extrapolation to lower temperatures and higher salinities of the non-linear S–t functions that describe the existing empirical data set can result in sizeable errors in these computations (Brown et al., 2014). With this caveat in mind, the estimated in situ pH in sea ice brines has been reported to range between 7 and 10 (Delille et al., 2007; Gleitz et al., 1995; Miller et al., 2011a; Papadimitriou et al., 2007). Finally, the use of the traditional pH measurement techniques (potentiometry, spectrophotometry) at sub-zero temperatures and high salinities is challenging because of untested electrochemical behaviour of glass electrodes used in potentiometry, lack of experimental data for the optical parameters and dissociation constants of pH indicator dyes used in spectrophotometry, and lack of suitable calibration buffers compounding the uncertainties of both potentiometric and spectrophotometric methods at sub-zero temperatures and hypersaline conditions. The range of environmental conditions for which saline pH buffers have been characterized is $0$–$40 \, ^\circ C$ and $S = 20$–$40$ for the 2-amino-2-hydroxymethyl-1,3-propanediol (Tris) compound in synthetic seawater (DelValls and Dickson, 1998), as well as $5$–$45 \, ^\circ C$ and $S = 35$ for 2-amino-2-methyl-1,3-propanediol (Bis), tetrahydro-1,4-isoazoxine (Morpholine), and 2-amino-pyridine (Aminopyridine) (Miller et al., 1993), all on the total proton scale. Similarly, pH indicator dyes have typically been characterized at above-zero temperatures and $S < 40$ conditions on the total and free proton scales (e.g., Liu et al., 2011; Robert-Baldo et al., 1985), with a further extension of the dye data set on the free proton scale in NaCl solutions by Millero et al. (2009) to the full ionic strength spectrum up to NaCl saturation ($0.03 < I < 5.50 \, m$) at above-zero temperatures. Overall, there is currently no validated method for measuring pH at sub-zero temperatures or, especially, in the coupled sub-zero temperature and high salinity of sea ice brines, or at any temperature for $S > 40$ in multi-electrolyte media.

The aim of this work was to enable reliable measurement of pH in saline and hypersaline media at sub-zero temperatures. To this end, we determined the pH of Tris buffer solutions in corresponding salinity and temperature conditions. For this task, we extended the standard electrochemical protocol for pH buffer characterization to international standards in the Harned (hydrogen gas/silver/silver chloride) cell (Bates, 1973) described in the oceanographic pH literature (Campbell et al., 1993; DelValls and Dickson, 1998; Dickson, 1990a, 1990b; Millero et al., 1993). The electrochemical characterization of pH buffers is an essential first step in the characterization of pH indicator dyes for use in the spectrophotometric pH determination. The characterization of the pH indicator dye meta-Cresol Purple (mCP) with a microfluidic flow spectrophotometric cell in the same temperature and salinity ranges will be reported in a companion paper. The results relayed here will therefore promote the acquisition of high quality in situ measurements of pH in polar waters and sea ice brines, and will improve the confidence in future investigations of this parameter of the carbonate system in these environments.

2. Methods

The pH of equimolar and non-equimolar Tris buffers (pH$_{Tris}$) in synthetic seawater and brines was determined with the electrochemical Harned cell (Bates, 1973), the only rigorous method available for the characterization of primary buffer solutions (IUPAC, 2002). The characterization was conducted in the Marine Physical Laboratory, Scripps Institution of Oceanography, University of California, San Diego, USA. The determination of the pH$_{Tris}$ requires the determination of the standard potential of the Harned cell from e.m.f. measurements with pure HCl solutions, HCl solutions prepared in the synthetic medium, and in HCl solutions in the synthetic medium with Tris. Details of the all-glass type Harned cell, and the silver-silver chloride and hydrogen electrodes used in this study can be found in DeValls and Dickson (1998). The solutions were analysed in duplicate or triplicate at each HCl mobility in the Harned cells in a thermostated water-glycol bath. The bath temperature was controlled to 0.01 °C and all e.m.f. measurements were corrected to 1 atm hydrogen gas fugacity (DeValls and Dickson, 1998). We characterized the Tris–HCl buffer in the standard equimolar Tris/Tris–H$^+$ composition (0.08 mol kg$_{H_2O}^{-1}$ Tris, 0.04 mol kg$_{H_2O}^{-1}$ HCl) and in a less alkaline non-equimolar Tris/Tris–H$^+$ composition (0.06 mol kg$_{H_2O}^{-1}$ Tris, 0.04 mol kg$_{H_2O}^{-1}$ HCl) in synthetic high ionic strength multi-electrolyte solutions matching the ionic ratios of standard seawater and seawater-derived brines. The synthetic solutions were prepared gravimetrically using the recipe in Table 1, which was based on that of standard seawater ($S = 35$) in DeValls and Dickson (1998). All synthetic solutions were prepared with purified salts, to maximize stability in the electrochemical response of the Harned cell. All salts (NaCl, Na$_2$SO$_4$, KCl, CaCl$_2$, MgCl$_2$) were twice re-crystallized from reagent grade salts, air-dried, annealed at 200 °C, and (except for CaCl$_2$ and MgCl$_2$) were heated to 500 °C (10 h) (Dickson, 1990a; Millero et al., 1993). The CaCl$_2$ and MgCl$_2$ salts were used to prepare approximately 1 mol kg$^{-1}$ solution Ca$^{2+}$ and Mg$^{2+}$ working stock solutions.

Table 1

| Component | mol kg$_{H_2O}^{-1}$ | mol kg$_{solution}^{-1}$ |
|-----------|---------------------|-------------------------|
| NaCl      | 0.42762 – $m_1$     | 0.41262                 |
| Na$_2$SO$_4$ | 0.02927          | 0.02824                 |
| KCl       | 0.01058            | 0.01021                 |
| MgCl$_2$  | 0.05474            | 0.05282                 |
| CaCl$_2$  | 0.01075            | 0.01037                 |
| HCl       | $m_1$              | 0                       |
| Tris      | $m_2$              | 0                       |
| Cl$^-$    | 0.5692             | 0.5492                  |
| I         | 0.7225             |                         |

a) The molality ($m_0$, in mol kg$_{H_2O}^{-1}$) of the salts in synthetic brines of salinity $S > 35$ and ionic strength $I$, was calculated as $m_0 = m_{eq} I / I_{Harned}$, with $I_{Harned} = 19.9184 \, S / 1000$ (Brown et al., 2014). The concentration in mol kg$_{H_2O}^{-1}$ was calculated by summing the total salt mass ($\sum m_{mass}$) and multiplying each salt molality with the factor, 1000 / ($1000 + \sum m_{mass}$). b) The molalities of HCl and Tris were chosen independent of ionic strength. In cells (B) and (C), $m_2 = 0$; in cells (D) and (E), $m_2 = 2 \, m_1$ for equimolar Tris buffers.
which were used for the preparation of the synthetic media. The concentration of Ca$^{2+}$ and Mg$^{2+}$ in these stock solutions was determined gravimetrically with a relative standard deviation better than 0.1% by Mohr titration with 0.3 mol kg$^{-1}$ AgNO$_3$, itself standardized similarly against purified NaCl and KCl (Dickson, 1990a; Millero et al., 1993). The working stock HCl solution (approximately 1 mol kg$^{-1}$ solution) was prepared gravimetrically with de-ionized water from double-distilled 6 M HCl solution. The concentration of these HCl solutions was determined by coulometry with a relative standard deviation better than 0.001%. It is standard practice to adjust the e.m.f. measurements in synthetic salt solutions so that their standard potential corresponds to that of Bates and Bower (1954). The adjustment factor is determined from e.m.f. measurements in dilute HCl solutions as described in the next section.

3. The standard potential of pure HCl solutions

The standard potential ($E_0$ = e.m.f. at infinite proton dilution) of the cell

$$\text{Pt: H}_2(\text{g, 1 atm})/\text{HCl}(m_1), \text{De-ionized Water}/\text{AgCl}, \text{Ag}$$

was determined regularly to ensure conformity with the measurements by Bates and Bower (1954). The $E_0$ of cell (A) was derived by solving the Nernst equation as $E_0 = E + 2k \ln m_{\text{HCl}}$, where $E = \text{measured e.m.f.}$, $\gamma_{\text{HCl}}$ = mean activity coefficient of HCl, $m_{\text{HCl}} = m_1$ in cell (A), and $k = $ gas constant = 8.31451 J mol$^{-1}$ K$^{-1}$. $T =$ absolute temperature (in K), and $E =$ Faraday constant = 96,485.31 C mol$^{-1}$. The $\gamma_{\text{HCl}}$ were computed as a function of ionic strength and temperature using the Pitzer parameterization. In the Pitzer formalism (Pitzer, 1973), the mean activity coefficient of HCl as an 1–1 electrolyte is calculated as $\ln \gamma_{\text{HCl}} = f' + m_{\text{Cl}}(\beta_{\text{HCl}}' + m_{\text{SO}_4} \chi_{\text{HCl}}' + \gamma_{\text{HCl}}' + m_{\text{Cl}}(\beta_{\text{HCl}} + m_{\text{SO}_4} \chi_{\text{HCl}} + \gamma_{\text{HCl}}))$, with $f' = -\frac{a^2}{b} \left[\frac{1}{(1+b^{0.2})} + \frac{2}{(b)} \ln (1+\frac{b}{2})\right]$, $\beta_{\text{HCl}}' = 4(\gamma_{\text{HCl}}')(\alpha - 1)\left(1+\frac{\alpha}{2}\right)$, and $\gamma_{\text{HCl}}' = 0.25(\gamma_{\text{HCl}}')$ where $\alpha = 2.0$ and $b = 1.2$, while molality ($m$) and ionic strength ($I$) are in mol kg$^{-1}$.$\text{H}_2\text{O}^{-1}$. The Pitzer coefficients, $A$, $B$, $\alpha$, $\beta_{\text{HCl}}$, $\chi_{\text{HCl}}$, and $\gamma_{\text{HCl}}$, were all computed from the temperature functions in Millero (2009). At the HCl molality and ionic strength (both 0.010 mol kg$^{-1}$) and temperatures used most frequently in this study for the $E_0$ determination, $\gamma_{\text{HCl}} = 0.9046$ at 25 °C and 0.9083 at 0 °C.

The $E_0$ determined in this study as described above ($E_{0\text{measured}}$) and by Bates and Bower (1954) ($E_{0\text{BB}}$) as computed from the temperature function in Dickson (1990b) yielded the offset $\Delta E_{0\text{BB}} = E_{0\text{measured}} - E_{0\text{BB}}$. At the temperatures that $E_{0\text{measured}}$ was determined in this study, $E_{0\text{BB}}$ was 0.22240 V at 25 °C, 0.23408 V at 5 °C, and 0.23659 V at 0 °C. To determine $\Delta E_{0\text{BB}}$, cell (A) was run on several occasions in parallel with the cells with synthetic saline and hypersaline media described in the next two sections. On average, $\Delta E_{0\text{BB}} = -0.00012 \pm 0.00024$ V (n = 39) with $m_{\text{HCl}} = 0.010$ mol kg$^{-1}$.$\text{H}_2\text{O}$ and $\Delta E_{0\text{BB}} = -0.00052 \pm 0.00016$ V (n = 4) with $m_{\text{HCl}} = 0.005$ mol kg$^{-1}$.$\text{H}_2\text{O}$ in cell (A) at 0, 5, and 25 °C during Harned cell runs with $S = 35$ synthetic seawater, while $\Delta E_{0\text{BB}} = 0.00000 \pm 0.00005$ V (n = 37) with $m_{\text{HCl}} = 0.010$ mol kg$^{-1}$.$\text{H}_2\text{O}$ in cell (A) at 0 and 25 °C during Harned cell runs with $S = 45–70$ synthetic brines, and $\Delta E_{0\text{BB}} = +0.00002 \pm 0.00005$ V (n = 17) with $m_{\text{HCl}} = 0.010$ mol kg$^{-1}$.$\text{H}_2\text{O}$ in cell (A) at 0 and 25 °C during Harned cell runs with $S = 85–100$ synthetic brines. To adjust the e.m.f. measurements in synthetic salt solutions so that their standard potential corresponds to that of Bates and Bower (1954), the average $\Delta E_{0\text{BB}}$ per group of saline and hypersaline Harned cell runs was subtracted from all e.m.f. measurements in these media. The adjusted e.m.f. measurements and the $\Delta E_{0\text{BB}}$ values used for their adjustment are reported in Table S1 in Supplementary Information for cells (B) and (C) and in Table 3 for cells (D) and (E); these cells are described in the next two sections.

4. The apparent standard potential of the Harned cell with synthetic seawater ($S = 35$) and synthetic brines ($S > 35$)

The e.m.f. measurements in the cells

Pt: H$_2$(g, 1 atm)/HCl(m$_1$), Synthetic Seawater(S = 35)/AgCl, Ag

Pt: H$_2$(g, 1 atm)/HCl(m$_1$), Synthetic Brine(S = 35)/AgCl, Ag

were used to determine their apparent standard potential ($E'_0$) in the presence of sulphate in the synthetic solutions of this study. Sulphate ions react with protons to form bisulphate (SO$_4^{2-} + H^+ = HSO_4^-$), with a stoichiometric dissociation constant $K_{\text{HSO}_4} = m_{\text{H}^+} m_{\text{SO}_4^{2-}}/m_{\text{HSO}_4^-}$. In this case, instead of the free proton scale ($m_{\text{H}^+}$), the total proton scale has been used previously defined, as $m_1 = m_{\text{H}^+} + m_{\text{SO}_4^{2-}} = m_{\text{H}^+} (1 + m_{\text{SO}_4^{2-}}/K_{\text{HSO}_4})$, with $m_1 = m_{\text{HCl}} = m_1$ in cells (B) and (C) above (Campbell et al., 1993; Dickson, 1990b). Thermodynamically rigorous, the total proton scale is suitable for the determination of acidity constants (Dickson, 1990b) and, as per objective of this study, is also used here to define and determine the pH of Tris buffers in keeping with previous studies (Campbell et al., 1993; DelValls and Dickson, 1998). Conversion to the free proton scale requires knowledge of $K_{\text{HSO}_4}$, which is not available at below-zero temperatures. It is beyond the scope of this study to determine $K_{\text{HSO}_4}$ because it is not needed to determine acidity constants in the total proton scale; as outlined below, this parameter is incorporated in the determined $E'_0$ term of the Nernst equation for cells (B) and (C).

The $E'_0$ is given by re-arrangement of the Nernst equation as $E'_0 = E_0 - 2k \ln m_{\text{HCl}} + k \ln (1 + m_{\text{SO}_4^{2-}}/K_{\text{HSO}_4}) = E + k \ln (m_{\text{HCl}}/m_{\text{SO}_4^{2-}})$ (Campbell et al., 1993; Dickson, 1990b; Millero et al., 1993). Here, $E$, $E'_0$, and $\gamma_{\text{HCl}}$ are as explained in the previous section, $K_{\text{HSO}_4}$ and $m_{\text{SO}_4^{2-}}$ as above, $m_{\text{H}^+} = total$ sulphate molality, $m_{\text{Cl}^-} = total$ chloride molality, and $E = measured$ e.m.f. in cells (B) and (C) above adjusted by $\Delta E_{0\text{BB}}$. The value of $E'_0$ in cells (B) and (C) was calculated from the adjusted $E_{0\text{measured}}$ value of the synthetic brines at ice-brine equilibrium, $S_A = 1000(1−54.11t)^{−1}$ (Assur, 1958).

5. Determination of the pH$_{\text{Tris}}$ in synthetic seawater ($S = 35$) and synthetic brines ($S > 35$)

The values of $E'_0$ in cells (B) and (C) (Table 2) were combined with e.m.f. measurements in cells (D) and (E) below, adjusted by $\Delta E_{0\text{BB}}$ as described in the previous sections, to determine at each salinity and temperature the value of pH$_{\text{Tris}}$ in mol kg$^{-1}$ solution as $pH_{\text{Tris}} = (E'_0 − \log(10))/\log(1−0.00106 S)$ (DelValls and Dickson, 1998) (Table 3). In this equation, ln10 is the conversion factor between
The apparent standard potential \(E^\circ\) of the reaction \(\text{AgCl} + \text{H}^+ + \text{e}^- \rightarrow \text{Ag} + \text{HCl}\) was derived from the stoichiometric equilibrium of the Tris-H+ dissociation reaction (Millero, 2009), with \(pK_{\text{Tris}}\) derived from the Henderson – Hasselbalch equation (Pratt, 2014), \(pH_{\text{Tris}} = pK_{\text{Tris}} + \log R_{\text{Tris}}\), which is derived from the stoichiometric equilibrium of the Tris-H+ dissociation reaction (Millero, 2009), with \(pK_{\text{Tris}}\) equivalent to the equimolal \(pH_{\text{Tris}}\) when \(R_{\text{Tris}} = 1\).

The \(E^\circ\) and \(pH_{\text{Tris}}\) data from this study alone and combined with relevant data at above-zero temperatures from earlier studies were fitted to non-linear equations of temperature and salinity or ionic strength using the Regression function in the Data Analysis Tool of Excel. The fitted coefficients of these equations, along with the adjusted squared correlation coefficient \((r^2)\) and the standard error of the fit \(s_{\text{fit}}\), as well as the number of fitted observations \(n\), are all reported from the Regression output in subsequent sections. Information about the standard error of the individual fitted coefficients is reported in Tables S2 and S3 in Supplementary Information.

6. Results

The focus of this study was the characterization of the \(pH\) of Tris buffers at below-zero temperatures but e.m.f. measurements were also obtained at 25 and 0 °C for evaluation relative to the existing datasets at overlapping temperature and salinity ranges. We kept this
The current \( E_{\text{tr}} \) values at below-zero temperatures and \( S = 35 \) were reported to have a significant effect on the pH measurement at sub-zero temperatures and \( S = 35 \) were different by \( +0.003 \) to \( +0.006 \) V different from those predicted by extrapolation of the equations in Dickson (1990b) and Campbell et al. (1993), respectively (Table 2). These differences are equivalent to 0.002–0.011 pH unit for the Tris buffer in synthetic seawater. A revised non-linear function of temperature is given below for \( E_{\text{tr}} \) in synthetic seawater (\( S = 35 \)) from the regression fit to the combined past and current data from 55 to \(-1.7^\circ C \) (\( T^2 = 0.99995, p < 0.0001, n = 27, \sigma_p = 0.00004 \V; the fitted residuals are shown in Fig. S1a in Supplementary Information), with \( E_0 = \) the Bates and Bower (1954) standard potential of the Harned cell as fitted by Dickson (1990b) and \( T = \) temperature (in K):

\[
E_0^{\ast} - E_0 = 0.583228 - 1.594057 \times 10^{-2}T + 2.529012 \times 10^{-1}T \ln T - 1.1284 \times 10^{-6}T^2.
\]

The difference between the current \( E_0^{\ast} \) values in the synthetic brines (\( S \geq 45 \)) and the extrapolated values from the existing equations (Table 2) ranged from \(+0.00020 \) to \(+0.00670 \) V (equivalent to 0.003–0.118 pH unit), increasing with increasing salinity throughout the experimental temperature range (Fig. 2). The current measurements provide for a more accurate and reliable measurement of the pH in ice-brine systems. To facilitate this application, we combined the \( E_0^{\ast} \) value at the freezing point of seawater derived from Eq. (1) above (\( E_0^{\ast} = 0.25340 \V \) at \(-1.93^\circ C \) and \( S = 35 \) at 1 atm total pressure) with the values obtained at the different freezing points of \( S \geq 45 \) brines (Table 2) to obtain a best-fit temperature function of \( E_0^{\ast} \) applicable to thermally equilibrated sea ice brines. We found \( E_0^{\ast} \) to be best described (\( r^2 = 0.98906, p = 0.00005, n = 7, \sigma_p = 0.00015 \V; the fitted residuals are shown in Fig. S1b in
Supplementary Information) by a quadratic function of temperature (T, in K) at the freezing point of seawater and seawater-derived brines from \(-1.93\) to \(-6.00\) °C (S = 35–100):

\[
E_o/C_{3o} = -11.632112 + 8.7319058 \times 10^{-2}T - 1.60345606 \times 10^{-4}T^2.
\] (2)

An extended equation is provided below for the computation of \(E_o^{\ast}\) by interpolation at any salinity and temperature outside the restricted conditions of Eqs. (1) and (2) above but within the limits of the experimental range. The interpolation will be useful for the characterization of pH buffers (on the total proton scale) on such occasions. Although the current \(E_o^{\ast}\) data set is sparse as a function of temperature, it was combined with the data sets in Dickson (1990b) and Campbell et al. (1993) for an overall best fit \(r^2 = 0.99186, p < 0.00001, n = 133, \sigma_{fit} = 0.00008\) V in the function format of the previous studies in ionic strength (I, in molality) and temperature (T, in K), with \(E_o\) from Dickson (1990b) as before:

\[
E_o^{\ast} - E_o = (0.8416344 - 2.0574375 \times 10^{-2}T + 3.1544753 \times 10^{-3}T \ln T - 2.6635 \times 10^{-8}T^2)^{0.5} + (-0.3356577 + 7.581873 \times 10^{-3}T - 1.1680967 \times 10^{-7}T \ln T)I + (1.1146 \times 10^{-2} + 4.525 \times 10^{-5}T)I^{1.5} - 4.67174 \times 10^{-3}I^2,
\] (3)

In the above equation, the ionic strength was calculated as a function of salinity as described in Table 1, while the fitted residuals are shown in Fig. 3. Eq. (3) is valid at temperatures (i) between 0 and 55 °C for I \(\leq 0.7225\) m (S \(\leq 35\)), (ii) between the freezing point and 55 °C for \(0.7225\) m \(\leq I \leq 0.9387\) m (35 \(\leq S \leq 45\)), and (iii) between the freezing point and 25 °C for \(0.9387\) m \(\leq I \leq 2.2136\) m (45 \(\leq S \leq 100\)). At 25 °C...
and I = 0.7225 m, Eq. (3) yields $E_o' = 0.24627$ V, while at $-6 \degree C$ and I = 2.2136 m, $E_o' = 0.25145$ V (see Table 2 for observed values).

6.2. The pH of Tris buffers to the freezing point of synthetic seawater and brines

The pH values of the equimolal Tris buffer are listed in Table 3 and are shown in Fig. 4. The equimolal pH$_{Tris}$ in synthetic seawater at 25 $\degree C$ and 0 $\degree C$ from the observed $E_o'$ (Table 2) and the e.m.f. measurements in cells (D) and (E) (Table 3) was within 0.002 pH unit from the values computed from the salinity and temperature function in DelValls and Dickson (1998) based on their experimental measurements at $S = 20$–40 and 0–45 $\degree C$. The equimolal pH$_{Tris}$ in synthetic seawater at sub-zero temperatures differed by 0.000–0.004 pH unit from the values obtained from the extrapolated DelValls and Dickson (1998) equation. The best-fit temperature ($T$, in K) function based on the combined current and previous data sets from 45 $\degree C$ to the freezing point of $S = 35$ seawater ($r^2 = 0.999997$, $p < 0.00001$, $n = 121$, $\sigma_{fit} = 0.001$ pH unit; the fitted residuals are shown in Fig. S2a in Supplementary Information) is given by the following equation:

$$pH_{Tris}^{(equimol)} = -322.08663 + 10570.47 T^{-1} -1.0408523 \times 10^{-1} T + 57.17485 \ln T,$$  (4)

The equimolal pH$_{Tris}$ in synthetic brines ($S \geq 45$) was determined up to $S = 70$. It was within 0.007 pH unit at $S = 45$ and 50 from the values predicted from the extrapolation of the DelValls and Dickson (1998) function but was lower than the extrapolated values by 0.009–0.019 and 0.021–0.036 pH unit at $S = 60$ and 70, respectively, at all examined temperatures, suggesting increasingly unsuitable values from extrapolation at high salinities regardless of temperature (Fig. 4). Combining the value of the equimolal pH$_{Tris}$ at the freezing point of $S = 35$ seawater from Eq. (4) above (equimolal pH$_{Tris}$ = 9.0039 at $-1.93 \degree C$) with the observations obtained at the different freezing points of $S \geq 45$ brines (Table 3), the equimolal pH$_{Tris}$ at ice-brine thermal equilibrium was found to be best described ($r^2 = 0.999929$, $n = 9$, $p < 0.00001$, $\sigma_{fit} = 0.002$ pH unit; the fitted residuals are shown in Fig. S2b in Supplementary Information) to $-4 \degree C$ and $S = 70$ by the following function of temperature ($T$, in K):

$$pH_{Tris}^{(equimol)} = -300435.6052 + 7240100.99 T^{-1} -99.5850583 T + 53678.964954 ln T,$$  (5)

The non-equimolal pH$_{Tris}=0.5$ values are given in Table 3 and are shown in Fig. 4. On the occasions when both the equimolal and the non-equimolal buffers were measured ($35 \leq S \leq 70$), the non-equimolal pH$_{Tris}=0.5$ values were within 0.001 pH unit from those determined from the Henderson–Hasselbalch equation described in the earlier section Determination of the pH$_{Tris}$ in synthetic seawater ($S = 35$) and synthetic brines ($S > 35$). The pH$_{Tris=0.5}$ at the freezing point was determined for $50 \leq S \leq 100$ and $-6.0 \degree C \leq t \leq -2.8 \degree C$. The best-fit function of temperature ($T$, in K) for the non-equimolal pH$_{Tris}=0.5$ in the temperature and salinity conditions of thermally equilibrated seawater-derived brines is as follows ($r^2 = 0.99991$, $n = 13$, $p < 0.00001$, $\sigma_{fit} = 0.001$ pH unit; the fitted residuals are shown in Fig. S2c in Supplementary Information):

$$pH_{Tris=0.5} = -725997.4416 + 1744719.73 T^{-1} -241.432111 T + 129781.87456 ln T,$$  (6)

As mentioned at the beginning of the Results section, there can be occasions when the measurement of pH in cold media, such as sea ice brines, may not be possible at below-zero temperature. To provide interpolation power for these occasions, the data sets of the equimolal

![Fig. 4](image-url) The pH of Tris buffer solutions (on the total proton scale) in synthetic seawater and synthetic brine as a function of salinity in panels (a) and (b), and as a function of temperature at sub-zero temperatures in panel (c). The observations from this study are from the equimolal Tris buffer (+) (molality ratio, $R_{Tris} = m_{Tris}/m_{Tris\text{-eq}} = 1$) and the non-equimolal Tris buffer (○) ($R_{Tris} = 0.5$). The solid line represents the best-fit Eq. (18) of DelValls and Dickson (1998) within its experimental salinity and temperature ranges, while the dashed line represents its extrapolation to $S < 20$ and $S > 40$, and below-zero temperatures. In panel (c), the temperatures below the freezing point of $S = 35$ seawater ($-1.93 \degree C$; dotted vertical line) represent the freezing points at $S > 35$ salinities.
pH$_{\text{Tris}}$ from this study and the study of DelValls and Dickson (1998) were combined to obtain a best fit in the format of the latter study, valid at temperatures (i) between 0 and 45 °C for S < 35, (ii) between the freezing point and 45 °C for 35 ≤ S < 45, and (iii) between the freezing point and 25 °C for 45 ≤ S ≤ 70. The best fit equation in salinity (S) and temperature (T, in K) (r$^2 = 0.999995$, n = 273, p < 0.00001, σ$_{fit} = 0.001$ pH unit; the fitted values are shown in Fig. 5a, c) is

$$\text{pH}_{\text{Tris}}\text{(equimolal)} = 536.08338 - 54.732367 S + 0.8518518 S^2$$
$$+ (0.1675218 - 1.72224095 \times 10^{-2} S$$
$$+ 2.66720246 \times 10^{-4} S^2) T + (-1.0873.5234$$
$$+ 1369.56485 S - 21.34442 S^2) T^{-1}$$

At 25 °C and S = 35, Eq. (7) yields pH$_{\text{Tris}}$ (equimolal) = 8.094, while at −4 °C and S = 70, pH$_{\text{Tris}}$ (equimolal) = 9.191 (see Table 3 for observed values). The equivalent overall fit on the current limited non-equimolal pH$_{\text{Tris}=0.5}$ data set yielded the following function of salinity and temperature (T, in K) at 50 ≤ S ≤ 100 and from the freezing point of such brines to 25 °C (r$^2 = 0.99999$, n = 41, p < 0.00001, σ$_{fit} = 0.002$ pH unit; the fitted residuals are shown in Fig. 5b, d):

$$\text{pH}_{\text{Tris}=0.5} = 144.4361 - 1.0809685 S + 6.023772 \times 10^{-3} S^2$$
$$+ (6.1841 \times 10^{-5} - 8.1739 \times 10^{-4} S + 4.27187 \times 10^{-6} S^2) T$$
$$+ (-27.233738 + 0.2329236 S - 1.281138 \times 10^{-3} S^2) \ln T$$

Using Eq. (8) above, the predicted pH$_{\text{Tris}=0.5}$ = 8.637 at 0 °C and S = 35, and pH$_{\text{Tris}=0.5}$ = 8.664 at 0 °C and S = 45. These values were within 0.004 pH unit from the measured values (Table 3), and so it is reliable to extend Eq. (8) to these salinities.

7. Discussion

The investigation of the carbonate system in oceanic waters and the determination of the potential for air-sea CO$_2$ exchange have intensified in an attempt to understand the implications on global climate of the increase in the atmospheric CO$_2$ since the industrial revolution. The required sampling and analytical protocols have been improved through continual method and instrument development, allowing dense sampling in space and time for any pair of the 4 measurable parameters of the carbonate system (TA, DIC, pH, fCO$_2$) (DOE, 1994; Hales et al., 2004; Liu et al., 2011). While the measurement of all 4 parameters is now routine in open ocean waters (e.g., Miller et al., 2002), including polar waters (Bates and Mathis, 2009; Bates et al., 2006), the same is not true for oceanic environments at sub-zero temperatures, such as sea ice. At the salinity and temperature conditions in sea ice brines, the concentrations of TA and DIC, as well as fCO$_2$ naturally cover large ranges controlled by the physical concentration of seawater solutes during the freezing of seawater and further cooling of internal sea ice brines, dilution of brine solutes by meltwater during sea ice melt, biological activity, CaCO$_3$ precipitation and dissolution, and CO$_2$ gas exchange (Delille et al., 2007; Dieckmann et al., 2008; Gleitz et al., 1995; Miller et al., 2011a, 2011b; Munro et al., 2010; Papadimitriou et al., 2012; Papadimitriou et al., 2007; Papadimitriou et al., 2004). By extension, large variations in brine pH can also be expected in such environments, but there is only rudimentary knowledge of pH changes in sea ice as direct determination of this parameter has been hampered by lack of characterized calibration standards (buffers, indicator dyes) and unsuitable analytical set-ups for the sub-zero temperatures and, in the case of internal sea ice brines, highly saline conditions (S > 35).

Currently, the pH measurement protocols in sea ice and sub-zero temperature oceanic waters, restricted by the temperature limitation of both buffers and technique, have only been capable of pH measurements at (constant) above-zero temperature. For example, Delille et al. (2007) used commercial glass electrodes and high salinity Tris and Aminopyridine buffers for instrument calibration on samples returned
Arctic Ocean, pH ranges from 7.7 to 12.1 in frost scale, pHns in seawater brines (S = 68) from the Henderson-Hasselbalch equation and the data presented here for investigations of the temperature and salinity ranges of this study. The pHf of the Tris-HCl buffers was increasingly alkaline with increasing salinity at constant temperature and with decreasing temperature at constant salinity (Table 3; Fig. 4). The equimolar Tris buffer covered a pHf range from 8.09 at S = 35 and 25 °C to 9.19 at the freezing point of an S = 70 synthetic brine (−4 °C) (Table 3). This pHf of the non-equimolar (Rtris = 0.5) Tris buffer ranged from 8.63 at S = 35 and 0 °C to 9.06 at the freezing point of an S = 100 synthetic brine (−6 °C) (Table 3) and was 0.3 pH unit less alkaline than its equimolal counterpart (Fig. 4) as predicted using the stoichiometric Tris-HCl equilibrium and the Henderson-Hasselbalch equation. On the strength of this evidence and the study of Pratt (2014) in synthetic seawater, Tris-HCl buffers of varying Rtris and, hence, pHf can be prepared if needed with the protocol outlined in Methods, and their pHf can be estimated reliably with the Henderson-Hasselbalch equation and the data presented here for investigations of the temperature and salinity ranges of this study.

The pHf ranges for the equimolar and non-equimolar (Rtris = 0.5) Tris buffers covered the alkaline spectrum of pH estimates at in-situ (below-zero) temperatures in sea ice. Delille et al. (2007) reported pHf values ranging from 8.4 to 9.4 in Antarctic fast ice brines (S = 24–89). In scaffold brines from the Weddell Sea, Antarctica, Papadimitriou et al. (2007) determined a pHbrine (seawater propane scale) range of 8.4 to 8.8, while Gleitz et al. (1995) reported a pHbrine range of 7.8 to 9.9. Hare et al. (2013) reported pHf values between 7.1 and 9.5 in frost flowers, bulk ice cores, and brines from artificial sea ice grown at an outdoors experimental facility. In the Arctic Ocean, pHf ranged from 7.7 to 12.1 in frost flowers and sea ice brines (Fransson et al., 2013), and from 8.3 to 8.5 (free proton scale, pHf) in scaffold brines (S = 68–163) (Miller et al., 2011a) in the Amundsen Gulf, while Rysgaard et al. (2012) reported pHf values between 9.9 and 10.1 in sea ice meltwater. In all these previous field studies, the pHf values at in situ (below-zero) temperatures have been computed from measured TA and DIC in sea ice environments (Brown et al., 2014; Papadimitriou et al., 2009; Papadimitriou et al., 2007) or from the pH measured directly in the sea ice medium at above-zero temperatures and either TA or DIC (Brown et al., 2014; Delille et al., 2007; Fransson et al., 2013; Gleitz et al., 1995; Hare et al., 2013; Miller et al., 2011a). In those instances, the pH at in situ (below-zero) temperatures has been derived by solving the system of equations that describe the thermodynamic relationships of the marine carbonate system (DOE, 1994) but with the caveat that the relevant equilibrium constants have not yet been characterized at sub-zero temperatures. Therefore, the use of this approach and the derived pH at the in situ (below-zero) temperatures rely on extrapolation of the existing oceanographic salinity and temperature functions of the equilibrium constants with discouragingly large uncertainties (Brown et al., 2014).

The electrochemical characterization of the Tris buffer system in this study enables the spectrophotometric characterization of pH indicator dyes in seawater-based hypersaline media at below-zero temperatures. Both techniques and their results will free the sea ice biogeochemical community from the uncertainty in the measurement of pH in sea ice by affording investigators direct pH determination in sea ice brines down to −6 °C and salinity 100. Sea ice has been found to become impermeable at a porosity <5% (as relative brine volume), coincident with a sea ice temperature of −5 °C at a bulk sea ice salinity of 5 (Cox and Weeks, 1975; Golden et al., 1998), or colder in more saline bulk sea ice, and vice versa, based on the phase relationships in the medium (Cox and Weeks, 1983). Hence, sea ice in the current experimental temperature range (−2 ≤ t ≤ −6 °C) is permeable to material transport via the brine channels. As a result, the current experimental conditions are pertinent to the study of the exchange potential of the brine carbonate system in sea ice with the underlying ocean and the atmosphere above.

Major compositional changes in the internal brine in sea ice will occur at temperatures well below −6 °C as a result of extensive precipitation of hydrated salts, such as mirabilite, gypsum, and hydrohalite (Butler et al., 2016; Butler and Kennedy, 2015; Marion, 2001). Consequently, a different logistical approach is required for the study of the brine carbonate system in the coldest compositional spectrum in sea ice, which is nearest to the atmosphere. Further work below the minimum temperature presented here must take into account mineral dynamics in sea ice for the determination of the chemical composition of the internal brines, which will inform the composition of synthetic or natural solutions to be used in the laboratory for the characterization of pH buffers and indicator dyes.

8. Conclusions

The current data set established explicitly the value of one of the important parameters in the study of the carbonate system, the pH of the Tris-HCl buffer system, in sub-zero temperature saline environments and within international standards. The pH of the Tris buffer was fully characterized on the total proton scale in the temperature range from 25 °C to the freezing point of S = 35 seawater (freezing point: −1.93 °C) and seawater-derived brines up to a salinity of 100 (freezing point: −6.0 °C). The difference between measurements at sub-zero temperatures and the extrapolated values computed from the existing above-zero temperature data sets may be negligible at S = 35 in terms of both the apparent standard potential of the electrochemical Harned cell and the equimolal pHHarned but increased systematically with increasing salinity at all temperatures. Based on the apparent standard potential of the Harned cell, this discrepancy was found to be equivalent to 0.118 pH unit at the highest salinity investigated here (S = 100), a substantial deviation with consequent discrepancies in other parameters of the carbonate system derived from it relying on extrapolation of existing electrochemical and oceanographic data sets defined for above-zero temperatures and S = 0–50. Hence, the current data will provide considerable improvement in the study of pH in cold saline and hypersaline conditions relative to the only choice of extrapolation available until now to biogeochemists. For a more complete characterization of the carbonate system in the cryosphere, the dissociation constants of its weak acids and bases (e.g., carbonic and boric acids) must be determined at below-zero temperatures.

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Appendix A. Supplementary data

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