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ORIGINAL PAPER

An Equation of State for Hypersaline Water in Great Salt Lake, Utah, USA

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Abstract Great Salt Lake (GSL) is one of the largest and most saline lakes in the world. In order to accurately model limnological processes in GSL, hydrodynamic calculations require the precise estimation of water density (ρ) under a variety of environmental conditions. An equation of state was developed with water samples collected from GSL to estimate density as a function of salinity and water temperature. The ρ of water samples from the south arm of GSL was measured as a function of temperature ranging from 278 to 323 degrees Kelvin (^{o}K) and conductivity salinities ranging from 23 to 182 g L^{-1} using an Anton Paar density meter. These results have been used to develop the following equation of state for GSL ($\sigma = \pm\ 0.32$ kg m^{-3}):

$$\rho - \rho^0 = 184.01062 + 1.04708 * S - 1.21061 * T + 3.14721E - 4 * S^2 + 0.00199T^2 - 0.00112 * S * T,$$

where ρ^0 is the density of pure water in kg m^{-3}, S is conductivity salinity g L^{-1}, and T is water temperature in degrees Kelvin.

Keywords Density · Conductivity · Great Salt Lake · Salinity · Terminal lake

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1 Introduction

The GSL, in the western United States, is a terminal lake with a surface area that can exceed 5,100 km^2. The lake is bordered on the west by desert and on the east by the Wasatch Mountain Range (Fig. 1). The GSL watershed encompasses 37,500 km^2 and contains a population exceeding 1.7 million people. Great Salt Lake is one of the most saline lakes in the world with salinities that can exceed 250 g L^{-1} (Sturm 1980). Prior to 1959, GSL was a continuous and relatively homogenous body of saline water; however, the completion of a railroad causeway in 1959 divided GSL into a north and south arm (Fig. 1) and significantly changed the water and salt balance (Loving et al. 2000). About 90% of the freshwater surface inflows enter GSL south of the railroad causeway resulting in consistently higher salinities in lake water north of the railroad causeway that can approach and exceed halite saturation.

Salinity variations in the south arm of GSL are also dependent on the changes in lake elevation. For the time period of 1850–1987, the salinity in the south arm ranged from a high of 27% to a low of 6% (Stephens 1990). The lowest salinity levels in the south arm were coincident with large increases in lake elevation during 1983–1984 (Stephens 1990).

Density stratification in the south arm of GSL was first observed in 1965 (Hahl and Handy 1969) and has been maintained by movement of higher salinity, north arm water into the south arm via three openings in the rock-filled railroad causeway (Fig. 1). The

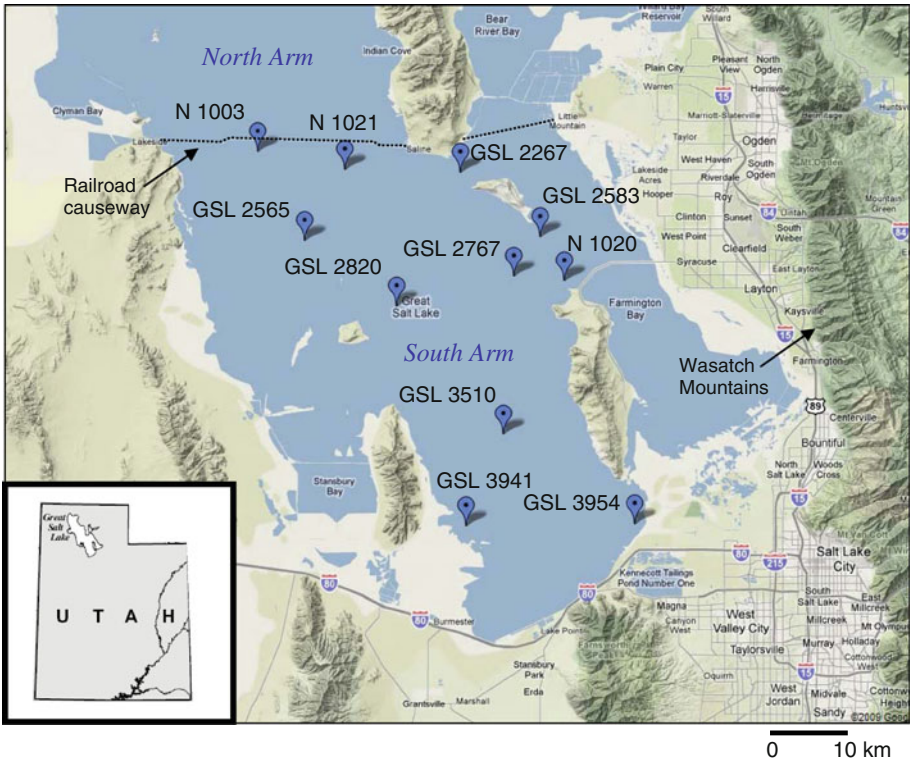

Fig. 1 Location of monitoring sites where salinity and density samples were collected during June 2009, Great Salt Lake, Utah

more saline brine layer in the south arm, commonly referred to as the deep brine layer (DBL), is not subject to annual turnover and can persist for multiple annual cycles (Gwynn 2002). The limited turnover of the DBL has resulted in anoxic conditions, promoting high rates of sulfate reduction (Ingvorsen and Brandt 2002) and high concentrations (>30 ng L^{-1}) of methylmercury (Naftz et al. 2008).

The major ion composition of water in GSL depends primarily on the variable balance between evaporation and input from the three major rivers (Bear, Weber, and Jordan Rivers), which provide more than 90% of the inflow to the lake. All of the inflow waters are fundamentally of the calcium bicarbonate type, but vary somewhat characteristically in the secondary major constituents (Jones et al. 2009). Evaporation and associated natural and human influenced in-lake processes have resulted in a Na–Cl-type brine in the modern day GSL. In addition to solute input from natural weathering, recent riverine input to GSL contains increasing amounts of industrial, urban, mining, and agricultural pollution from within the watershed (Naftz et al. 2000). Recent pollutants of concern include mercury (Naftz et al. 2008, 2009a), selenium (Beisner et al. 2009; Diaz et al. 2009a, b; Naftz et al. 2009b; Oliver et al. 2009), and nutrients (Marcarelli and Wurtsbaugh 2005; Wurtsbaugh et al. 2009).

The physical and chemical properties of natural brines have been studied in other saline systems including the Dead Sea (Krumgalz and Millero 1982), Red Sea (Millero et al. 1982), and Mono Lake (Jellison et al. 1999). The equation of state developed for water from the Dead Sea provided reliable estimates of density (ρ); however, ρ was also found to be very sensitive to small changes in ionic composition (Krumgalz and Millero 1982). Relationships among conductivity, temperature, total dissolved solids, and density were determined in hypersaline brine samples from Mono Lake. The equation of state based on

Table 1 Measured relative densities of samples at 298.15°K collected in Great Salt Lake and normalized relative density to measured salinity

Sample	Sample depth	S	$\rho-\rho^0$	Del[a]
N1003	Shallow	133.318	100.627	−0.161
N1003	Deep	134.642	101.589	−0.200
N1020	Shallow	118.140	88.632	−0.682
N1021	Shallow	133.167	100.536	−0.138
N1021	Deep	134.934	101.821	−0.189
GSL 2267	Shallow	128.063	96.582	−0.234
GSL 2565	Shallow	134.206	101.273	−0.187
GSL 2565	Deep	181.968	139.876	2.308
GSL 2583	Shallow	127.834	96.279	−0.364
GSL 2767	Shallow	135.250	102.001	−0.248
GSL 2820	Shallow	136.564	103.021	−0.221
GSL 3510	Shallow	138.406	104.714	0.079
GSL 3510	Deep	144.835	109.606	0.111
GSL 3941	Shallow	139.792	105.634	−0.049
GSL 3954	Shallow	136.101	102.934	0.042

[a] The difference in the measured densities minus the values calculated from 0.756 * S based on the average ratio of $(\rho-\rho^0)/S = 0.756 \pm 0.004$. Units are in kg m^{-3}

[Shallow, sample depth 0.2 m below water surface; deep, sample depth 0.5 m above lake bottom; S, measured salinity in g L^{-1}; ρ, measured density in kg m^{-3}; ρ^0, calculated density of pure water, in kg m^{-3}]

Table 2 Measured densities of Great Salt Lake water as a function of temperature

Sample	Sample depth	S	T (°K)	ρ (kg m^{-3})
N1003	Shallow	133.318	278.35	1105.3
			283.15	1103.2
			288.15	1101.2
			293.15	1099.1
			298.05	1097.7
			302.95	1095.4
			307.65	1093.1
			312.25	1090.9
			318.05	1087.9
			321.75	1086.1
N1003	Deep	134.642	278.35	1105.9
			283.15	1104.3
			288.15	1102.6
			293.15	1100.7
			298.15	1098.7
			303.15	1096.6
			308.15	1094.1
			313.15	1091.8
			318.15	1089.2
			323.15	1087.1
N1020	Shallow	118.140	278.15	1092.7
			283.15	1090.8
			288.15	1088.9
			293.15	1087.0
			297.85	1085.6
			302.75	1083.6
			307.05	1081.4
			312.25	1078.6
			317.45	1076.1
			321.65	1074.2
N1021	Shallow	133.167	278.15	1104.9
			283.15	1103.1
			288.15	1101.1
			293.15	1098.9
			298.05	1097.6
			303.05	1095.3
			307.35	1093.1
			312.15	1091.0
			317.95	1087.8
			321.75	1086.1
N1021	Deep	134.934	278.15	1106.1
			283.15	1104.7
			288.15	1102.8
			293.15	1100.9

Table 2 continued

Sample	Sample depth	S	T (°K)	ρ (kg m^{-3})
			298.15	1098.9
			303.15	1096.9
			308.15	1094.4
			313.15	1092.2
			318.15	1089.8
			323.15	1087.4
GSL 2267	Shallow	128.063	278.45	1100.8
			283.15	1099.3
			288.15	1097.5
			293.35	1095.6
			298.15	1093.6
			303.15	1091.5
			308.05	1088.8
			312.85	1086.5
			317.25	1084.1
			323.15	1081.8
GSL 2565	Shallow	134.206	278.15	1105.6
			283.15	1104.1
			288.15	1102.2
			293.15	1100.3
			298.15	1098.4
			303.15	1096.2
			308.15	1093.3
			313.15	1091.2
			317.65	1088.6
			323.15	1086.4
GSL 2565	Deep	181.968	278.55	1145.4
			283.15	1143.4
			288.15	1141.5
			293.15	1139.3
			298.15	1137.1
			303.15	1134.8
			308.15	1132.1
			313.15	1129.7
			318.15	1127.1
			323.15	1124.2
GSL 2583	Shallow	127.834	278.65	1100.4
			283.15	1098.9
			288.15	1097.2
			293.35	1095.3
			298.15	1093.3
			303.15	1091.3
			308.15	1088.8
			313.15	1086.4

Table 2 continued

Sample	Sample depth	S	T (°K)	ρ (kg m^{-3})
			318.15	1084
			323.15	1080.6
GSL 2767	Shallow	135.250	278.15	1106.4
			283.15	1104.9
			288.15	1103.0
			293.15	1101.1
			298.15	1099.1
			303.15	1096.9
			308.15	1094.4
			313.15	1092.0
			318.15	1089.3
			323.15	1086.6
GSL 2820	Shallow	136.564	278.45	1107.6
			283.15	1105.5
			288.15	1103.5
			293.15	1101.5
			298.05	1097.7
			302.95	1095.4
			307.65	1093.1
			312.25	1090.9
			318.05	1087.9
			321.75	1086.1
GSL 3510	Shallow	138.406	278.15	1109.3
			283.15	1107.7
			288.15	1105.8
			293.15	1103.7
			298.15	1101.8
			303.15	1099.7
			308.15	1097.0
			313.15	1094.5
			317.95	1091.7
			322.65	1090.0
GSL 3510	Deep	144.835	278.15	1114.3
			283.15	1112.5
			288.15	1110.8
			293.15	1108.8
			298.15	1106.7
			303.15	1104.5
			308.15	1101.8
			313.15	1099.2
			317.55	1096.9
			323.15	1093.9
GSL 3941	Shallow	139.792	278.55	1109.9
			283.15	1108.5

Table 2 continued

Sample	Sample depth	S	T (°K)	ρ (kg m^{-3})
			288.15	1106.6
			293.35	1104.7
			298.15	1102.6
			303.15	1100.6
			308.15	1098.2
			313.15	1095.7
			317.85	1093.0
			323.15	1091.0
GSL 3954	Shallow	136.101	278.65	1107.3
			283.15	1105.7
			288.15	1103.9
			293.25	1102
			298.15	1100
			303.15	1097.9
			308.15	1095.5
			313.15	1093
			318.15	1090.2
			323.15	1088.5

[S, measured salinity in g L^{-1}; T (°K), sample temperature, in degrees Kelvin; ρ, measured density in Kg m^{-3}; shallow, sample depth 0.2 m below water surface; deep, sample depth 0.5 m above lake bottom]

temperature and conductivity was found to best estimate measured water density (Jellison et al. 1999).

Most studies of natural brines have focused on the measured densities relative to the ionic interactions of the major components in the brines (Millero 2009). The U.S. Geological Survey (USGS) has intermittently monitored the density and conductivity of water in GSL at the Saltair marina (U.S. Geological Survey 2009); however, there have been no site-specific studies focusing on vertical and horizontal density structures and how these structures change over short—(minutes to days) and long-term (days to months) time scales. In order to accurately model limnological processes in GSL, hydrodynamic calculations require the precise estimation of ρ under a variety of environmental conditions

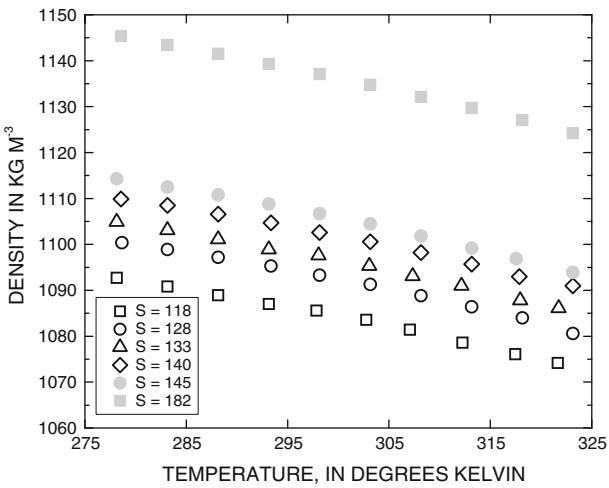

Fig. 2 The density of water samples from Great Salt Lake as a function of temperature for salinities (S) ranging from 118 to 182 g L^{-1}

(Ji 2008). The ρ is a function of temperature (T), salinity (S), and total suspended sediment (C) and is referred to as the equation of state. The objective of this paper is to develop an equation of state for GSL that can be integrated into existing limnological modeling software to accurately characterize the spatial–temporal changes in vertical and horizontal ρ structure to better simulate in-lake hydrodynamic and mixing processes.

2 Methodology

2.1 Field Methods

Surface-water samples from each of the lake sites were collected during June 2009 by submerging a prerinsed, 4-L polycarbonate bottle approximately 0.2 m below the lake

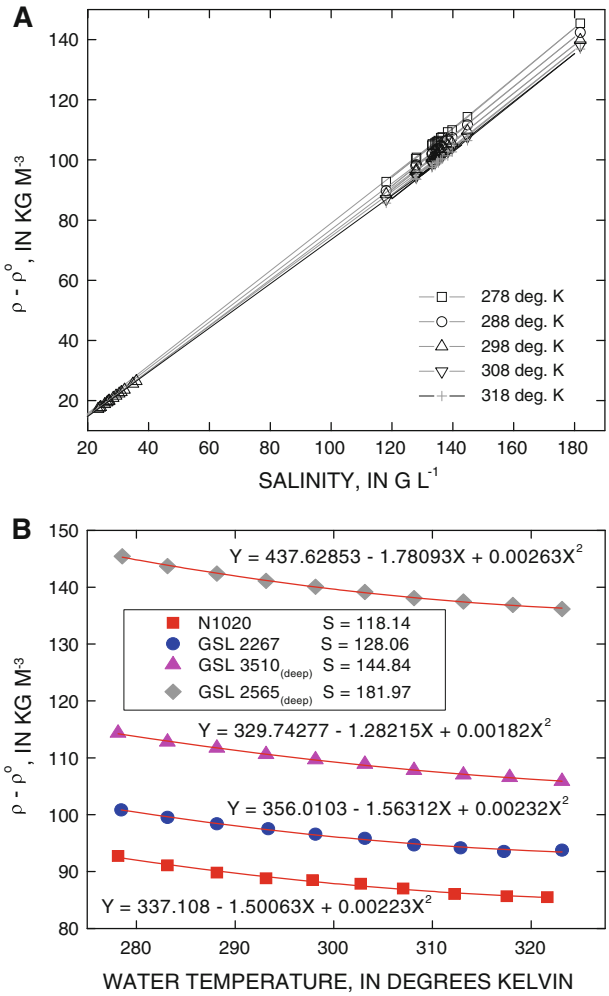

Fig. 3 Measured relative density ($\rho - \rho^0$) of water samples from Great Salt Lake as a function of (**a**) salinity and (**b**) temperature. Salinity (S) in g L^{-1}

surface. Samples of the more saline DBL (approximately 7 m below the lake surface and representing water from the north arm) were collected using a 2-L Wildco vertical water bottle that was sealed at the desired sampling depth using a weighted messenger. After collection, water samples were filtered (<0.45 μm pore size) on site and stored in 1-L glass bottles with polyseal caps until analysis.

2.2 Laboratory Methods

The ρ of water samples was measured with an Anton Paar DMA 35 density meter at $T =$ (278.15 to 323.15) °K. The instrument was calibrated with air and water. The density of pure water (ρ^0) was taken from Spieweck and Bettin (1992), which is based on the equations of Kell (1975) corrected to the 1990 temperature scale:

$$\begin{aligned}\rho^0 = [&999.83952 + 16.952577(T - 273.15) - 7.9905127\mathrm{E} - 03(T - 273.15)^2 \\ &- 4.6241757\mathrm{E} - 05(T - 273.15)^3 + 1.0584601\mathrm{E} - 07(T - 273.15)^4 \\ &- 2.8103006\mathrm{E} - 10(T - 273.15)^5]/[1 + 0.016887236(T - 273.15)]\end{aligned} \quad (1)$$

where T is in °K. Water sample temperature was varied from 278 to 323°K using a constant temperature bath.

The conductivity or practical salinities of the samples were measured with a Guideline Salinometer at the University of Miami's Rosenstiel School of Marine and Atmospheric Science. The salinometer was calibrated with standard seawater. Measurements of the density of standard seawater agreed to values determined from the equation of state of Millero and Poisson (1981) to ± 0.002 kg m^{-3}.

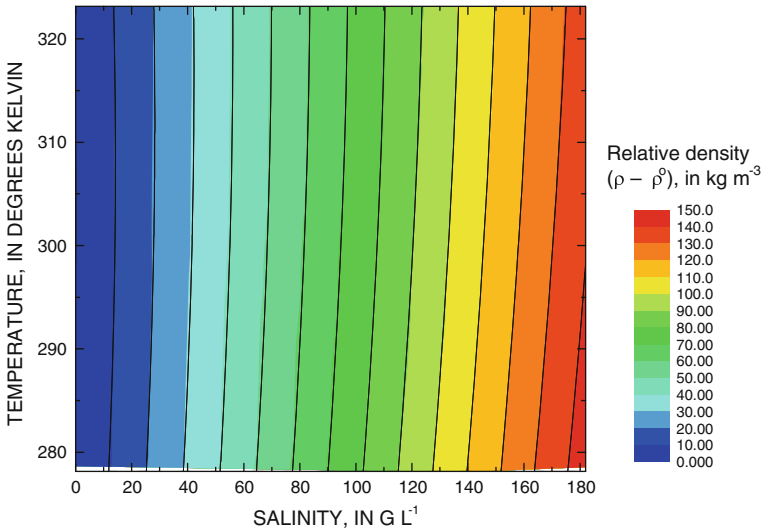

Fig. 4 Modeled relative density ($\rho - \rho^0$) of water from Great Salt Lake as a function of salinity and temperature

3 Results and Calculations

The salinity and relative densities ($\rho-\rho^0$) of the 15 samples collected from the south arm of GSL and measured at 298.15°K are shown in Table 1. Measured salinities ranged from $\sim$ 118 at a site receiving freshwater inflow to $>$ 180 g L^{-1} for a sample of the DBL. The relative densities were normalized to the measured salinity according to ($\rho-\rho^0$)/S, resulting in a ratio of 0.756 $\pm$ 0.004 (Table 1). This ratio was used to calculate relative densities and compare the calculated versus measured relative densities to examine the internal consistency of the water samples (Table 1). With the exception of the DBL sample from site GSL 2565, all the samples agree within $\pm$ 0.682 kg m^{-3}. The larger discrepancy between calculated and measured relative density for the DBL sample from site GSL 2565

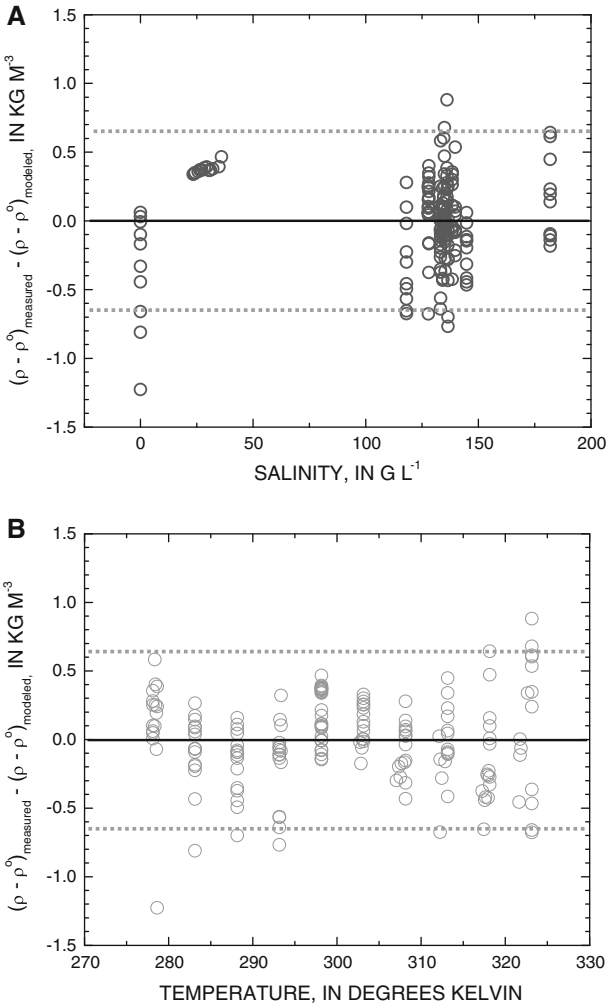

Fig. 5 Differences between the measured and modeled relative density ($\rho-\rho^0$) of water from Great Salt Lake as a function of (**a**) salinity and (**b**) temperature. *Dashed lines* designate $\pm 2\sigma$

exhibits the influence of the higher salinity water from the north arm of GSL. The larger discrepancy calculated for the DBL sample suggests that a separate equation of state may be required for the higher salinity water in the north arm of GSL.

Changes in ρ as a function of temperature (278 to 323°K) are listed in Table 2 and shown in Fig. 2 for selected salinities (118, 128, 133, 140, 145, and 182 g L^{-1}). Quadratic equations best represent the changes in ρ as a function of temperature for the range of salinity values shown in Fig. 2.

The relative densities of water from GSL are a near-linear function of salinity at varying temperatures (Fig. 3a) and a quadratic function of temperature at varying salinities (Fig. 3b). A two variable, quadratic equation ($\sigma = \pm$ 0.32 kg m^{-3})

$$\rho - \rho^0 = 184.01062 + 1.04708 * S - 1.21061 * T + 3.14721E - 4 * S^2 + 0.00199T^2 - 0.00112 * S * T \quad (2)$$

was used to model ($\rho - \rho^0$) as a function of both salinity and temperature. The fitted curves of Eq. 2 (equation of state for GSL) for salinity ranging from 0 to 180 g L^{-1} and temperature ranging from 278 to 323°K are shown in Fig. 4.

Differences between the measured and modeled ($\rho - \rho^0$) from Eq. 2 (equation of state) are compared to the 2 standard deviations (σ) (Fig. 5). The observed differences are within the 2σ ($\pm$ 0.64 kg m^{-3}) and do not show any notable bias with respect to either temperature or salinity (Fig. 5). Additional data are needed to determine if the current equation of state will be valid for increasing salinities in GSL under different environmental conditions (for example, lower lake elevations).

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