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NOTE

A new method for temperature compensation of electrical conductivity using temperature-fold dependency of fresh water

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Abstract A new method for temperature compensation of electrical conductivity (EC) is proposed. A relationship between temperature and EC was investigated in detail by a simple experiment using natural and artificial fresh water. Results showed that the temperature dependency of EC varied from 0.03 to 0.02, with temperature increasing from 3°C to 35°C. This means that a traditional method for compensating for EC using a constant coefficient is invalid, so that a temperature-fold dependency must be taken into consideration to standardize EC to a common temperature.

Keywords Electrical conductivity · Temperature compensation · Temperature-fold dependency · Fresh water

Introduction

Electrical conductivity (EC) or specific conductance (SC) is widely measured as the important water quality indicator or tracer, which roughly represents the total number of ions dissolved in water. It has been well known that the EC or SC depends on water temperature; it is increased by approximately 2% with temperature increase of 1°C (e.g., IHS 1985; Japanese Industrial Standards Committee 1999; Hayashi 2004). The following method has been widely applied to compensate EC value to a standard temperature, such as 18°C or 25°C:

$$\begin{aligned} EC_{18} &= EC_t/\{1+\alpha(t-18)\} \\ \text{or } EC_{25} &= EC_t/\{1+\alpha(t-25)\} \end{aligned} \quad (1)$$

where EC_{18}, EC_{25} and EC_t are the EC values at temperature 18°C, 25°C and t°C, respectively, and α is the coefficient which means temperature dependency of EC. The value of α is usually assumed to be a constant value around 0.02.

In this article, it will be shown by some simple experiments that the temperature dependency α of fresh water must be a function of temperature, and thus the formula (Eq. 1) is not valid for the compensation of EC.

Materials and methods

We measured the EC values of water sampled at the surface (0.5 m-depth) and in the deep layers (40 m depth) of Lake Biwa by changing the water temperature in steps of approximately 1°C from 3°C to 35°C in the laboratory. Two containers with different volumes were prepared: a small container filled with sampled water was set inside a large one into which approximately 5 l of water was poured. The temperature of about 3 l of water sample was controlled by a thermostat, and ice or hot water was used to change the temperature of the surrounding water in the large container. The temperature and raw value of the EC of the water samples were occasionally measured, with accuracies of 0.1 μS cm^{-1} by EC meter (TOA DKK CM21P) and 0.01°C by standard thermometer (TOA enclosed-scale type). The automatic compensation function of the EC meter was not used in the experiments.

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Results and discussion

An example of experimental results for the Lake Biwa water is shown in Fig. 1. Using this result, we calculated temperature dependency of EC as a function of temperature by:

$$\alpha(t) = 0.5(\mathrm{EC}_{t+\Delta t} - \mathrm{EC}_t)/(\mathrm{EC}_{t+\Delta t} + \mathrm{EC}_t)\Delta t.$$

Here t, $\alpha(t)$ and Δt are water temperature, temperature dependency coefficient and small temperature change, respectively. The dependency coefficient $\alpha(t)$ is rather high, around 0.03 in cold water, whereas it is low, about 0.02, in warm water (Fig. 2a). This means that $\alpha(t)$ is no more than a constant value, which has long been considered, but is a function of temperature. This relationship (Fig. 2a) is well assumed to be a linear function of $\alpha(t) = at + b$, with $a = -3.58 \times 10^{-4}$ and $b = 3.04 \times 10^{-2}$. Figure 2b shows another result for tap water, and shows the same tendency as Fig. 2a.

In general, the temperature dependency of EC is represented as follows;

$$\mathrm{dEC}/\mathrm{d}t = \alpha(t) \times \mathrm{EC} \tag{2}$$

By integrating (Eq. 2) with temperature t, we obtain

$$\mathrm{InEC} = \int_t \alpha(t)\mathrm{d}t + c,$$

where c is an integral constant. This leads to a relationship between EC_{25} and EC_t such that

$$\ln(\mathrm{EC}_{25}/\mathrm{EC}_t) = \int_t^{25} \alpha(t)\mathrm{d}t$$
$$\therefore \mathrm{EC}_{25} = \mathrm{EC}_t \times \exp\left(\int_t^{25} \alpha(t)\mathrm{d}t\right). \tag{3}$$

From the experimental result of $\alpha(t) = at + b$ (see Fig. 2),

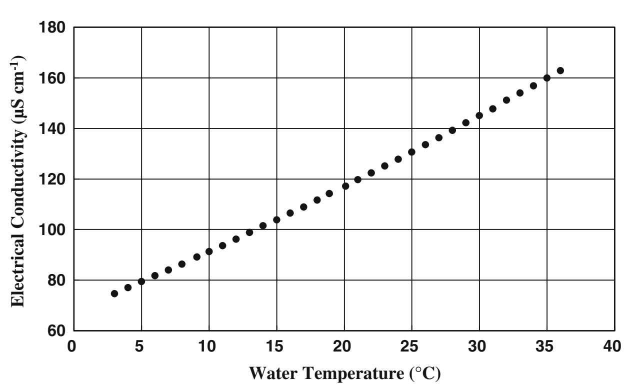

Fig. 1 An experimental result showing the water temperature–electrical conductivity relationship of Lake Biwa water

$$\mathrm{EC}_{25} = \mathrm{EC}_t \times \exp\left(\int_t^{25} (at + b)\mathrm{d}t\right)$$
$$\therefore \mathrm{EC}_{25} = \mathrm{EC}_t \times \exp\left\{0.5a\left(25^2 - t^2\right) + b(25 - t)\right\}. \tag{4}$$

This must be the precise equation to compensate for a temperature effect of EC instead of the formula (Eq. 1). Practically, the procedure of correction of EC to the 25°C value is easy by using

$$\mathrm{EC}_{25} = \beta(t) \times \mathrm{EC}_t. \tag{5}$$

In the case of Lake Biwa water,

$$\beta(t) = 5.75 \times 10^{-4}t^2 - 5.02 \times 10^{-2}t + 1.89,$$

using $a = -3.58 \times 10^{-4}$ and $b = 3.04 \times 10^{-2}$ in Eq. 4. The values of $\beta(t)$ for a given temperature of every 1°C are shown in Table 1.

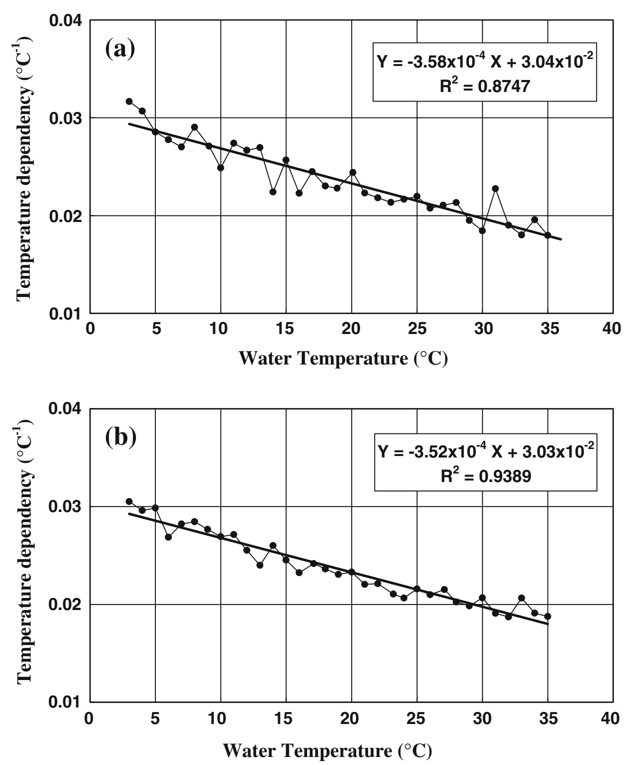

Fig. 2 Temperature dependency of electrical conductivity versus water temperature in **a** Lake Biwa water and **b** tap water

Table 1 Temperature dependency coefficient $\beta(t)$ at given temperature t for EC_{25}, which is obtained from $\mathrm{EC}_{25} = \beta(t)\cdot\mathrm{EC}_t$

°C	0	1	2	3	4	5	6	7	8	9
0	1.90	1.85	1.79	1.74	1.69	1.65	1.60	1.56	1.51	1.47
10	1.43	1.40	1.36	1.33	1.29	1.26	1.23	1.20	1.17	1.14
20	1.12	1.09	1.07	1.04	1.02	1.00	0.98	0.96	0.94	0.92
30	0.90	0.88	0.87	0.85	0.84	0.82				

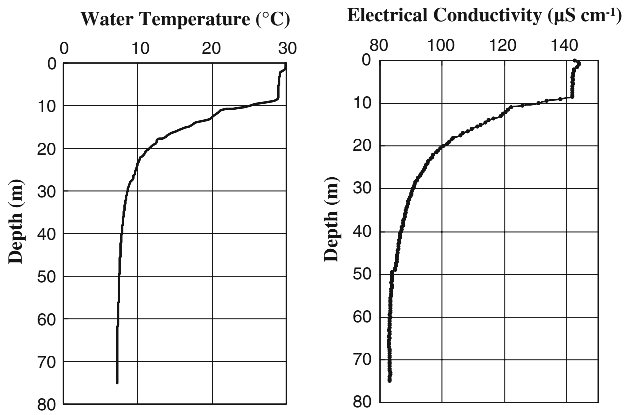

Fig. 3 Vertical profiles of water temperature and electrical conductivity observed in the north basin of Lake Biwa on 16 August 2006

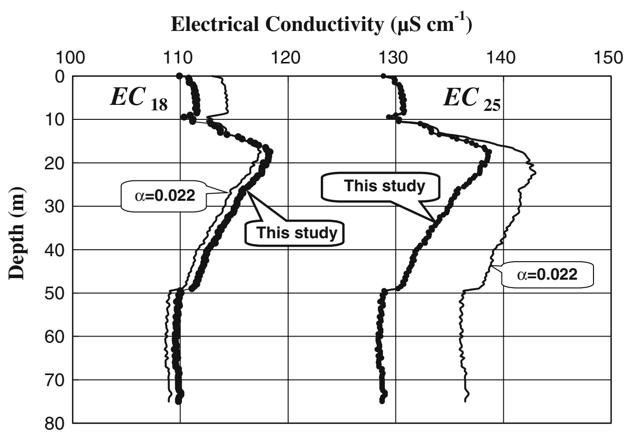

Fig. 4 The thermally compensated EC_{18} and EC_{25} profiles from the constant α (= 0.022) and temperature-fold $\alpha(t)$ derived in this study

It must be noted that the traditional formula (Eq. 1) is invalid, even if $\alpha(t)$ is constant. In this case, Eq. 2 is expressed by using constant α as,

$$\ln \mathrm{EC} = \alpha t + c$$
$$\therefore \mathrm{EC}_{25} = \mathrm{EC}_t \times \exp\{\alpha(25 - t)\}. \quad (6)$$

If a value of $\alpha(25-t)$ is much smaller than 1, Eq. 6 coincides with the formula (Eq. 1) by the mathematical approximation of $\exp(x) \approx 1 + x$ $(x << 1)$. If the usual values of $\alpha = 0.02$ and $t = 0$ are applied, it yields $\alpha(25-t) = 0.5$, which is not enough smaller than 1. Therefore, the formula (Eq. 1) is not valid to compensate for the EC value, even if the temperature dependency α is assumed to be a constant.

Figure 3 shows vertical profiles of water temperature and EC observed in Lake Biwa in summer. The thermally compensated EC_{18} and EC_{25} profiles from Eqs. 1 and 5, respectively, are shown (Fig. 4). It is quite obvious that the vertical profiles of EC_{18} and EC_{25} compensated for by Eq. 1 are very different from each other, i.e., the surface EC_{18} is larger than the bottom EC_{18}, whereas it is vice versa in EC_{25}. In contrast, the two profiles of EC_{18} and EC_{25} that are compensated for by the formula (Eq. 5) have the same tendency, except for an absolute values shift due to different standard temperatures of 18°C and 25°C.

In the case of seawater, the practical salinity scale is used to define the salinity, which is calculated by the EC of seawater (UNESCO 1981). The salinity and temperature of water are strongly related to the water density, which controls the water mixing and circulation in the oceans and lakes (UNESCO 1983). In this context, the accurate estimation of EC is very important to clarify the dynamics of water body.

As mentioned above, EC is also used in environmental monitoring as an indicator or a tracer of fresh water in lakes, rivers and ground water. Many commercial instruments for EC measurement have a function for automatic temperature compensation, using a constant α. However, we strongly request that these EC meters should be improved with regard to the compensation of temperature effect by using temperature-fold dependency $\alpha(t)$. Before this improvement can be achieved, EC_{18} or EC_{25} must be calculated by a formula (Eq. 5) from the measured raw value of EC without the use of the automatic compensation function of instruments.

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