Research Article

An Underwater Wireless Sensor Network with Realistic Radio Frequency Path Loss Model

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We propose an Underwater Wireless Sensor Network (UWSN) for near-shore applications using electromagnetic waves (EM). We also introduce a realistic path loss model for estimating the attenuation encountered by EM waves in underwater environments. The proposed model takes into account the variation of the seawater complex-valued relative permittivity with frequency in contrast to previous work that treats the permittivity as a real-valued constant parameter. Furthermore, the proposed model accounts for the impedance mismatch at the seawater-air boundary, which results in a more realistic estimate of the signal attenuation. Simulation results show the expected signal levels underwater for different scenarios. A prototype implementation to measure the path loss is also presented.

1. Introduction

There has been a great interest in developing underwater wireless communication systems using electromagnetic waves such as Underwater Wireless Sensor Networks (UWSNs). Such networks could be used for monitoring near-shore variations in seawater, coastal surveillance, autonomous underwater vehicle (AUV) operations, environmental research, and so forth [1]. The interest in EM underwater communications is motivated by several features such as the support of high data rates, and the low propagation delay. This will reduce the transmission duration, which will reduce the power consumption, and consequently it will prolong the lifetime of the nodes [2]. Also, EM waves are insensitive to the disturbances in the physical environment [1]. Moreover, the sensor nodes have become affordable in very large quantities as well as being self-operated. They can be randomly deployed over the region of interest (e.g., scattered by an airplane over a hostile environment). These advantages incur low installation and maintenance cost compared to the existing communication systems.

Acoustic waves, on the other hand, remain the prevalent existing underwater communication mechanism in deep aquatic environments since they can propagate for longer distances. However, for near-shore applications, significant human activities and ambient noise severely affect underwater acoustic communication systems (e.g., congested environments like harbours and ports). In addition, underwater acoustic channels are characterized by the harsh physical layer conditions, which result in low data rate capabilities, high propagation delay, and high bit error rate (BER). For instance, sound waves use very low frequencies for signal transmission, and thus have very limited bandwidth, which results in very low data rates. In addition, with a propagation speed of 1500 m/s, sound waves cause a significant delay in signal transmission. These aforementioned challenges limit the possible applications provided by acoustic systems. That is, it is impractical to implement acoustic systems for both near-shore applications and real-time applications [3].

To overcome the problems faced by acoustic wave based systems, cables are commonly deployed for reliable transmission near the shore. However, cable-based systems suffer from high cost of installation and frequent need of calibration and maintenance. Other solutions based on optical communications have also been proposed such as AquaOptical in [4] where several optical modems are developed for point-to-point communications underwater. However, the
long-range modem is currently very expensive (it costs around US$1,200), and thus it is implausible to implement for large-scale networks. A cheaper short-range modem is also developed, but it covers few meters and as well it has worse performance in terms of signal detection. Finally, it is observed in [4] that the turbidity of seawater severely limits the achievable data rates. In general, optical communication systems suffer from the need for accurate alignment between the optical transmitter and receiver, they are susceptible to particles and marine fouling (i.e., turbidity of seawater), and optical waves do not smoothly cross seawater-air boundary [1].

EM waves outperform both acoustic and optical waves in shallow water applications as they tolerate ambient noise, turbidity, and temperature changes. Furthermore, EM waves allow for much lower propagation delay and higher data rates (Mbps range) as compared to acoustic waves. These features support real-time applications where different forms of data could be transmitted (text, images, and videos), and hence new horizons for underwater applications become possible. For instance, UWSN could be deployed for AUVs where robots could get faster commands from the base station. It could be used for coastal surveillance where cameras could be distributed all over the shore at certain depths to monitor human activities, marine life, or any physical phenomenon. Other applications include monitoring of coastal erosion; prediction of natural disasters; and many other real-time applications that require high data rates. In addition, these sensors could be implemented as body area networks for divers to monitor their health, oxygen level, equipment, and so forth. All these features motivate the use of EM waves for both near-shore applications and real-time applications. Table 1 provides a brief comparison of the different underwater wireless communication systems.

| Propagation speed | Line of sight (LOS) | Impact of environment (ambient noise, turbidity, temperature changes, etc.) | Achievable data rates | Network coverage | Impact on marine life |
|-------------------|---------------------|-----------------------------------------------------------------------------|-----------------------|------------------|---------------------|
| EM waves          | Acoustic waves      | Optical waves                                                               |
| High              | Very slow           | High                                                                        | High                  | Short range      | Not known           |
| Not required      | Not required        | Required with precise alignment of nodes                                     |
| Minimal           | High                | High                                                                        |
| High              | Very low            | Very high                                                                   |
| Not known         | Very long range     | Very short range                                                             |

In this paper, we propose a UWSN for near-shore applications. We introduce a more realistic path loss model for EM waves propagating in seawater that considers both the variation of the seawater complex-valued relative permittivity with frequency and the impedance mismatch at the seawater-air boundary. The rest of this paper is organized as follows. Section 2 describes the proposed UWSN structure. Section 3 outlines the electric properties of seawater and their impact on the propagation of EM waves. The proposed underwater path loss model is developed in Section 4. Simulation and experimental results are presented in Section 5. Finally, conclusions are summarized in Section 6.

### 2. Proposed UWSN Description

The architecture of the proposed UWSN is shown in Figure 1. It is composed of different nodes that communicate using EM waves to send information from sensor nodes to a sink node through one or more intermediate nodes. The sensor nodes might be anchored at the seabed to collect application-specific data or could be moving, as the case for AUVs. The data is then transmitted to the intermediate nodes that are scattered in the coverage area of the UWSN. The intermediate nodes need to be anchored at different locations and heights within the area of interest. They receive the EM signal, amplify it, and then retransmit it again to other intermediate nodes. Finally, a buoy node receives the signal at the seawater surface and forwards it to the sink node. The block diagram of the system is shown in Figure 2.

The number and distances between intermediate nodes depend on the attenuation faced by the EM waves as they...
propagate through seawater. To cover the same area of interest, more nodes are required when using EM waves compared to acoustic waves (i.e., higher node density). This is due to the signal attenuation, which depends on the electric properties of seawater. Another important factor that also affects signal attenuation is the implementation of the buoy node. We consider two schemes for the buoy node design.

Scheme I uses one antenna at the buoy node that is not immersed in seawater, and hence the signal needs to cross the seawater-air boundary to be received by the buoy node. This results in significant attenuation of the signal, and hence needs more amplification at the intermediate nodes. To alleviate such a problem, Scheme II uses a buoy node with two antennas. The first antenna is immersed in seawater, and thus it receives the signal underwater from the intermediate nodes. Then, the buoy node amplifies the signal and then retransmits it to the sink through the second antenna, which is implemented above seawater. Scheme II provides for less attenuation, and therefore it is preferred to implement. All of these observations are going to be discussed in details in the next sections.

3. Electric Properties of Seawater

The propagation of EM waves in seawater is significantly different from that on air because seawater has distinct electrical properties that severely impact the signal propagation. Thus, in order to develop a realistic path loss model for EM wave propagation in seawater, these properties need to be discussed.

3.1. Conductivity. The conductivity of a medium affects the transmission of an EM wave through that medium. Specifically, the transmitted signal will face more attenuation as the conductivity of the medium increases. Seawater has high conductivity that varies depending on the presence of ions in it. For instance, the conductivity of Red Sea is 8 S/m whereas it is only 2 S/m in the Arctic. For typical seawater, it is common standard to use a value of 4 S/m for seawater conductivity [5, 8, 9]. This is 400 times higher than the conductivity of freshwater, which is typically around 0.01 S/m [7].

3.2. Permeability and Permittivity. Permeability is the ability of the medium to store magnetic energy. Since seawater is a nonmagnetic medium, it has the same permeability as free space, \( \mu_{\text{seawater}} = \mu_{\text{freespace}} [8] \). On the other hand, the relative permittivity, also known as the dielectric constant, describes the ability of a medium to transmit an electric field [8]. The relative dielectric permittivity of seawater (\( \varepsilon_r \)) is usually set to 81 [6, 9, 10]. However, this assumption is not accurate since the relative permittivity is in general complex-valued and depends on other factors such as the salinity of seawater, temperature, and carrier frequency [11]. Debye’s model considers all the factors that affect both the real and the imaginary part of the relative permittivity [12]. In this paper, salinity is assumed to be a constant value of 35 PSU, which is the average value measured by Dubai Coastal Zone Monitoring at the local shores of Dubai [13]. Figure 3 illustrates the variation of the real part of the dielectric constant of seawater with frequency at different temperatures. Thus, the assumption made by pervious work in [6, 10], that the real dielectric constant is a constant, regardless of the seawater temperature, is not realistic. Figure 3 shows also that, for all practical frequency range, it is safe to assume that the real part of the dielectric is constant. This statement, however, is not applicable to the imaginary part of the dielectric constant as shown in Figure 4. Although the imaginary part is independent of the temperature, it is relatively large at lower frequencies, yet it decreases exponentially as the frequency increases. Hence, the assumption made in [6] that the imaginary part of the dielectric constant is negligible is again not realistic. Thus, assuming a constant real part (independent of the temperature) as well as a negligible imaginary part for the dielectric constant would lead to inaccurate path loss model for EM waves in seawater (see the appendix for permittivity calculations).

3.3. The Intrinsic Impedance. The intrinsic impedance is a medium property that describes the ratio of the electric field strength (\( E \)) to the magnetic field strength (\( H \)) [8]. The
Real dielectric constant of seawater (salinity = 35 PSU).

Figure 3: The real dielectric constant of seawater (salinity = 35 PSU).

Imaginary dielectric constant of seawater

Figure 4: The imaginary dielectric constant of seawater (salinity = 35 PSU).

intrinsic impedance of air is found to be $\eta_0 \approx 377$ Ω. However, the intrinsic impedance of seawater is complex-valued, and it is expressed as

$$\eta = \frac{E}{H} = \sqrt{\frac{j \omega \mu}{\sigma + j \omega \varepsilon}},$$

where $\mu$ is the permeability, $\varepsilon$ is the permittivity, $\sigma$ is the conductivity, and $\omega = 2\pi f$ is the angular frequency. A complex intrinsic impedance indicates a phase difference between $E$ and $H$ in the transverse electromagnetic wave (TEM). Both the magnitude and the angle of intrinsic impedance of seawater are demonstrated in Figure 5. The phase difference is constant for a wide range of frequencies, $f \leq 100$ MHz, and it is equal to $\pi/4$, which is a typical phase difference in a conducting medium [8]. Figure 5 shows that the intrinsic impedance magnitude is relatively small compared to the impedance of air. Thus, the large impedance mismatch between seawater and air would cause significant signal reflections at the seawater-air boundary as indicated by the reflection coefficient.

The reflection coefficient is expressed as [8]

$$\Gamma = \frac{E_{\text{reflected}}}{E_{\text{incident}}} = \frac{\eta_0 - \eta_{\text{seawater}}}{\eta_0 + \eta_{\text{seawater}}},$$

and the transmission coefficient for normal incidence is defined as [8]

$$T = \frac{2\eta_0}{\eta_0 + \eta_{\text{seawater}}},$$

The reflection and transmission coefficients for seawater are demonstrated in Figure 6. Note that we have $T = 1 + \Gamma$.

4. Channel Model

For proper deployment of any wireless communication system, it is critical to have accurate channel characterization. Channel modeling provides important information about the received signal strength (i.e., path loss) and multipath structure. In terrestrial WSNs, with air as the propagation medium, numerous works have been done to develop realistic channel models. However, due to the aforementioned electric properties of seawater, direct relation between seawater and air cannot be established. Hence, we are motivated to propose a new model for the underwater channel.

Path loss is a fundamental parameter in characterizing the wireless channel. It represents the difference between the transmitted signal power and the received signal power [14]. Path loss represents a large-scale channel modeling because, in terrestrial wireless systems, it is observed for large distances (hundreds of wavelengths). However, in the proposed underwater network structure, the distances between the nodes are expected to be very small (few meters), but the path loss underwater would be comparable with the path loss of hundreds of meters in air as we will demonstrate in this section. The path loss considered in this work is expressed in dB as [7]

$$PL = L_{\alpha\varepsilon} + L_R,$$

where $L_{\alpha\varepsilon}$ is the attenuation loss in seawater due to seawater conductivity and complex permittivity (in dB), and $L_R$ is the reflection loss at the seawater-air boundary (in dB) due to the impedance mismatch between the two mediums.

In order to realize the impact of the complex permittivity on the attenuation factor, the attenuation loss is derived from the propagation constant $\gamma$, which is expressed as [8]

$$\gamma = j\omega \sqrt{\mu \varepsilon - j \sigma \varepsilon \omega} = \alpha + j\beta,$$
where \( \alpha \) is the attenuation factor (in Neper/m), and \( \beta \) is the phase constant per unit length. Taking the real part of the propagation constant, we obtain the attenuation loss (in dB) as

\[
L_{\alpha,\varepsilon} = \Re \left( \gamma \right) \times \left[ \frac{20}{\ln(10)} \times D \right],
\]

where \( D \) is the separation distance between the transmitting and the receiving nodes. Figure 7 illustrates the attenuation loss \( L_{\alpha,\varepsilon} \) with the variations of the carrier frequency. It is clear that the attenuation loss is very high, and this is due to the very high conductivity of seawater, which severely attenuates the propagating EM wave. Such property sets a tight constraint on the separation distance between the nodes.

Also, it is evident that the complex permittivity has a direct impact on the signal attenuation in seawater. We remark that the results of Uribe and Grote in [2] are originally made as a function of distance, and their model is tested for few frequencies with \( \sigma = 1 \). However, we used our parameters to make the comparison appropriate. Also, Al-Shamma'a et al. model in [6] is independent of seawater permittivity.

On the other hand, signal reflection due to impedance mismatch has a major impact on the EM wave propagation between different mediums. Impedance matching is very important to minimize the reflection at the boundary and maximize power transfer [8]. Since we have identified a mismatch in intrinsic impedance between seawater and air, a high-signal reflection at the boundary is expected. The transmitted power can be written as

\[
P_t = \Re \left\{ \frac{|E_i|^2}{2\eta_{\text{seawater}}} \right\} |T|^2e^{-2\alpha D},
\]

where \( E_i \) is the incident electric field and \( \eta_{\text{seawater}}^* \) is the conjugate of the intrinsic impedance of seawater. Hence, the reflection loss at the seawater-air boundary in dB can be shown to be

\[
L_{R} = 10 \log \left( |T|^2 \Re \left\{ \frac{\eta_0}{\eta_{\text{seawater}}} \right\} \right).
\]

From (4), the total path loss in dB is expressed as

\[
PL = \Re \left( \gamma \right) \times \left[ \frac{20}{\ln(10)} \times D \right] + 10 \log \left( |T|^2 \Re \left\{ \frac{\eta_0}{\eta_{\text{seawater}}} \right\} \right).
\]
careful changes must be made. Figure 8 illustrates the high-
signal attenuation at the seawater-air boundary. It shows that
the reflection loss decreases dramatically as the frequency
increases from 100 KHz to 1 GHz, and then it remains almost
constant for frequencies higher than 2 GHz. This could be
explained by noting that the magnitude of the intrinsic
impedance of seawater is directly proportional to the carrier
frequency; that is, as the frequency increases the impedance
of seawater increases as shown in Figure 5, and hence the gap
between the impedance of seawater and air decreases, which
will ultimately reduce the reflection losses at the boundary.
However, Figure 5 indicates that the impedance of seawater
converges to a constant value for further increase in the
operating frequency, and hence the reflection loss would
be approximately constant at those frequencies (\(f \geq 2\) GHz).
We remark that the significant reduction in the reflection
loss (up to 25 dB) could be tempting to operate the network
at the gigahertz range, but the total path loss is actually
much higher due to the attenuation caused by electric
properties of seawater. Figure 9 illustrates that the total path
loss, \(PL\), with frequency variations at different separation
distances between the transmitter and the receiver. Unlike
the reflection loss, the total path loss exponentially increases
with frequency because of the very high-attenuation losses
underwater. Also, it is clear that a small increase of the
separation distance would have a major impact on the total
loss, and hence, this would put stringent requirements on the
distance between the network nodes.

Finally, a comparison between our model and the model
presented in [7] is demonstrated in Figure 10. Both mod-
els implement Debye's models for seawater and freshwater,
respectively. It is observed that the high conductivity of
seawater drastically increases the path loss.

5. Simulation and Experimental Results

In this section, MATLAB simulations are presented for the
path loss and bit error rate (BER) for the proposed UWSN.

We assume that the sensor node is located at the seabed, and
the signal is sent directly to the buoy node located at the
surface of the water. The buoy node detects the transmitted
data and then retransmits it again to the sink node. Both cases
for a buoy node with nonimmersed antenna (scheme I) and
immersed antenna (scheme II) are simulated. Without loss of
generality, Quadrature Phase Shift Keying (QPSK) is used as
the modulation scheme with square root-raised cosine pulse
shape. The QPSK signal is then transmitted through a channel
with a path loss according to the model developed in (9). The
signal is also assumed to undergo flat fading with Rician
distribution since there are generally no obstacles between
the transmitter and receiver. The channel is also assumed
to have very slow variation with time (low Doppler) since the
mobility of the nodes is limited. The movement of the nodes
could be caused by the dynamic underwater environment
such as the water current or the movement of surrounding
objects. Using the data provided by Dubai Coastal Zone
Monitoring, the maximum current speed is approximately
equal to 0.2 m/s [13]. The Doppler shift is expressed as [14]

\[ \Delta f = \frac{f \cdot v_{rel}}{v}, \]  

where \( f \) is the transmitted signal frequency in Hz, \( v_{rel} \) is
the mobility of the surrounding environment relative to the
receiver in m/s, and \( v \) is the speed of the EM wave in seawater,
and it is given by [8]

\[ v = \frac{c}{\sqrt{\mu_r \varepsilon_r}}, \]  

where \( c \) is the speed of light, \( \mu_r \) and \( \varepsilon_r \) are the relative
permeability and relative permittivity of seawater, respectively.
Hence, the Doppler shift will be limited to about 0.15 Hz at
a carrier frequency of 25 MHz, which leads to slow fading
conditions [14, 15].

Figure 11 illustrates the received signal power for the
two schemes for a transmitter at a depth of 1 meter, and
a transmitted power of 0 dBm. It is clear that using an
immersed antenna at the buoy node significantly reduces the
signal power loss. This could be exploited either to increase
the distance between nodes or use a higher operating fre-
frequency to achieve higher data rates. The improvement in
the performance is mainly due to the elimination of the reflection
losses at the seawater-air boundary. Table 2 compares the path
loss of the two proposed schemes at different frequencies.
The path loss gap between the two schemes decreases as the
frequency increases because the reflection losses decrease at
higher frequencies. Nonetheless, it is evident that at any given
operating frequency, Scheme II is more power efficient. This
is very crucial since power management is one of the major
challenges in UWSN design, and hence by just making the
receiver antenna of the buoy node immersed in seawater, we
may prolong the battery life of the nodes, which in return, will
reduce the regular maintenance and the battery replacement
process. On the other hand, if we decide to send power at the
same level, we can further increase the separation distance
between the nodes (depending on the receiver sensitivity),
which in return, will either expand the communication range,
or reduce the number of nodes required to cover the same
coverage area. Figure 12 shows the BER performance for the
system with immersed antenna case. The result shows that
the BER improves as the energy per bit-to-noise power ratio
\( (E_b/N_0) \) increases.

Finally, we have implemented a prototype to measure the
path loss for the two schemes. A 1.2 \( \times \) 1.0 \( \times \) 1.0 m\(^3\) tank
is filled with seawater mixed with a small portion of freshwater.
The container is made up of Aluminum and covered with a
plastic sheet from the inside to ensure that the conductivity
of the surface is minimal. An antenna, which is insulated by
Nylon sheet is installed on the inner side of the container
at a height of 20 cm from the bottom surface. An arbitrary
function generator is connected to the underwater antenna,
and a signal is transmitted at different carrier frequencies. In
both schemes, the transmitted power is set to 11.8 dBm, and
the separation distance between the transmitter antenna and
the receiver antenna is 1.2 meters. The signal is detected at
the surface using spectrum analyzer. A comparison between
the path loss of Scheme I and Scheme II is shown in Figure 13.

The results confirm that the path loss of the external
receiver antenna is higher than the one with the immersed
antenna. This is due to the reflection at the surface as sug-
gested earlier. It is also clear that as the frequency increases,
the path loss increases in agreement with the simulation
results. We remark that our experimental results cannot
be compared directly with the simulation results for the
following reasons. First, the range of frequencies used is not
precisely within the available antennas’ operational range.

Table 2: Path loss comparison between the two schemes.

| Carrier frequency (MHz) | Scheme I (dB) | Scheme II (dB) | Path loss reduction (%) |
|-------------------------|---------------|----------------|-------------------------|
| 0.05                    | 25.3          | 10.9           | 71%                     |
| 0.1                     | 40.2          | 15.4           | 62%                     |
| 0.2                     | 45.1          | 21.8           | 52%                     |
| 0.5                     | 55.8          | 34.5           | 38%                     |
| 1                       | 68.6          | 48.8           | 29%                     |
| 2                       | 87.3          | 69.0           | 21%                     |
| 5                       | 125.3         | 109.0          | 13%                     |
| 10                      | 168.8         | 154.0          | 9%                      |
| 15                      | 202.3         | 188.4          | 7%                      |
| 20                      | 230.6         | 217.3          | 6%                      |
| 25                      | 255.4         | 242.6          | 5%                      |
Second, we have mixed a portion of freshwater with seawater, which in return will affect the salinity of the medium. Third, the temperature of the medium is different. We assumed a temperature of 25°C in the simulations. Nevertheless, the experiment provides insights on the importance of implementing an immersed antenna at the buoy node. It is clear from the experimental results that immersing the antenna significantly reduces the path loss (up to 20 dB which is also demonstrated in the simulation results). Another insight is that at higher frequencies, the gap between Scheme I and Scheme II reduces because the reflection loss is also decreased. This reduction is due to the fact that the intrinsic impedance of seawater increases as the frequency increases. Thus, the mismatch of impedances between seawater and air decreases. This is what we have also demonstrated theoretically and in the simulations.

6. Conclusion

In this paper, an underwater wireless sensor network using electromagnetic waves is proposed. A realistic model for the path loss underwater has been developed. The effect of the signal reflection at the seawater-air boundary has also been considered. Two schemes are proposed for the buoy node located at the surface of the water; one based on nonimmersed antenna and the other with immersed antenna. The proposed schemes are simulated under slow fading channel conditions, and both the path loss and bit error rate performance are presented. Finally, a prototype to measure the path loss is implemented.

Appendix

Permittivity Calculations

In saline water, the real dielectric constant is expressed as [12]

$$\varepsilon'_sw = \varepsilon_{sw,0} + \frac{\varepsilon_{sw,0} - \varepsilon_{sw,∞}}{1 + (2\pi f \tau_{sw})^2}$$

(A.1)

and the imaginary part is expressed as [12]

$$\varepsilon''_sw = \frac{2\pi f \tau_{sw} (\varepsilon_{sw,0} - \varepsilon_{sw,∞})}{1 + (2\pi f \tau_{sw})^2} + \frac{\sigma}{2\pi \varepsilon_0},$$

(A.2)

where $\varepsilon'_sw$ and $\varepsilon''_sw$ are the real and imaginary dielectric constants of saline water, respectively, $\varepsilon_{sw,0}$ is the static dielectric constant at low frequency, $\varepsilon_{sw,∞}$ is the dielectric constant at high-frequency limit, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the permittivity of free space, $\sigma$ is the conductivity, and $\tau_{sw}$ is the relaxation time. $\varepsilon_{sw,∞}$ is independent of salinity, and hence, $\varepsilon_{sw,∞} = \varepsilon_{water,∞} = 4.9$ [12]. Whereas $\varepsilon_{sw,0}$ depends on both the salinity ($S_{sw}$) and the temperature ($T$) according to the following relation

$$\varepsilon_{sw,0} (T, S_{sw}) = \varepsilon_{sw,0} (T, 0) \cdot a (T, S_{sw}),$$

(A.3)

where

$$\varepsilon_{sw,0} (T, 0) = 87.134 - 1.949 \times 10^{-1} T - 1.276 \times 10^{-2} T^2 + 2.491 \times 10^{-4} T^3,$$

$$a (T, S_{sw}) = 1 + 1.613 \times 10^{-5} T \cdot S_{sw} - 3.656 \times 10^{-3} S_{sw} + 3.21 \times 10^{-5} S_{sw}^2 - 4232 \times 10^{-7} S_{sw}^3.$$  

(A.4)

The relaxation time, on the other hand, is expressed as [12]

$$\tau_{sw} (T, S_{sw}) = \tau_{sw} (T, 0) \cdot b (T, S_{sw}),$$

(A.5)
where
\[
\tau_{sw}(T,0) = \frac{1}{2\pi} \left( 1.11 \times 10^{-10} - 3.824 \times 10^{-12} T \\
+ 6.938 \times 10^{-14} T^2 - 5.096 \times 10^{-16} T^3 \right),
\]
\[
b(T,S_{sw}) = 1 + 2.282 \times 10^{-2} T \cdot S_{sw} - 7.638 \times 10^{-4} S_{sw} \\
- 7.76 \times 10^{-6} S_{sw}^2 + 1.105 \times 10^{-8} S_{sw}^3.
\]
(A.6)

The temperature range is \(0 \leq T \leq 40^\circ C\) while the salinity range is \(4 \leq S_{sw} \leq 35\) PSU.

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