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Assessment of a vertical high-resolution distributed-temperature-sensing system in a shallow thermohaline environment

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Assessment of a DTS system
F. Suárez et al.

Title Page

Abstract | Introduction
Conclusions | References
Tables | Figures

◄ | ►
◄ | ►
Back | Close

Full Screen / Esc

Printer-friendly Version
Interactive Discussion

Abstract

In shallow thermohaline-driven lakes it is important to measure temperature on fine spatial and temporal scales to detect stratification or different hydrodynamic regimes. Raman spectra distributed temperature sensing (DTS) is an approach available to provide high spatial and temporal temperature resolution. A vertical high-resolution DTS system was constructed to overcome the problems of typical methods used in the past, i.e., without disturbing the water column, and with resistance to corrosive environments. This system monitors the temperature profile each 1.1 cm vertically and in time averages as small as 10 s. Temperature resolution as low as 0.035 °C is obtained when the data are collected at 5-min intervals. The vertical high-resolution DTS system is used to monitor the thermal behavior of a salt-gradient solar pond, which is an engineered shallow thermohaline system that allows collection and storage of solar energy for a long period of time. This paper describes a method to quantitatively assess accuracy, precision and other limitations of DTS systems to fully utilize the capacity of this technology. It also presents, for the first time, a method to manually calibrate temperatures along the optical fiber.

1 Introduction

Temperature fluctuations are a major driver of changes in natural and managed aquatic systems (Rosenzweig et al., 2007). In thermohaline aquatic environments such as estuaries or saline lakes, it is important to measure temperature on fine spatial and temporal scales to detect stratification or different hydrodynamic regimes. Spatial variability in shallow thermohaline systems can occur on vertical scales of centimeters and temporal variability occurs on time scales ranging from minutes to months, or even years (Anati and Stiller, 1991; Lorke et al., 2004; Lu et al., 2004; Kurt and Ozkaymak, 2006). Measuring temperature at these scales, especially when diel cycles need to

be recorded over a long time period, can be difficult because of the cost involved and other practical limitations (Branco et al., 2005).

In the past, two methods have been used frequently to measure temperature gradients within the water column: first, a temperature sensor that can move vertically, and second, an array of fixed sensors at different depths. The moving sensor has the potential to mix the water column due to the motion of the sensors, obscuring the temperature gradients. Slow-moving sensors can be used to avoid this, but the temporal resolution of slower sensors is degraded. Arrays of sensors can introduce scatter into the data due to calibration differences and bias between the sensors, and have limited spatial resolution.

Fiber-optic distributed temperature sensing (DTS) is an approach available to provide coverage in both space and time that can be used to continuously monitor real-time data in different environments. It was first developed in the 1980s (Dakin et al., 1985) and used in the oil and gas industry during the 1990s and early 2000s (Kersey, 2000); only since 2006 has it been widely used in hydrologic applications (Selker et al., 2006; Westhoff et al., 2007; Moffett et al., 2008; Tyler et al., 2009; Vogt et al., 2010). DTS technology uses Raman spectra scattering in a fiber-optic cable to measure temperatures along the cable length. The ratio between the anti-Stokes and Stokes wavelengths of the Raman scattering is used to estimate the temperature along the fiber, and the location of the temperature measurement along the cable is calculated using the travel times of the incident and scattered lights. A detailed description of the theoretical basis of DTS systems is out of the scope of this work and can be found elsewhere (Rogers, 1999; Selker et al., 2006). Commonly available DTS systems can achieve a temperature resolution as fine as 0.01 °C with typical spatial and temporal resolutions of 1–2 m and 10–60 s, respectively, for cables up to 10 km (Selker et al., 2006). However, there are hydrologic environments such as shallow (<2 m deep) lakes or ponds where thermal observations at smaller vertical scales are required (Losordo and Piedrahita, 1991; Branco and Torgersen, 2009; Suarez et al., 2010a). This has resulted in the development of vertical high-resolution DTS systems.

Assessment of a DTS system

F. Suárez et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The pioneering of a vertical high-resolution DTS system for hydrologic applications was presented by Selker et al. (2006). They monitored temperatures on a glacier and in a lake using an optical fiber wrapped around a 75 mm diameter 2 m length polyvinyl chloride (PVC) pole. Two platinum resistance thermistors (PT100), located at the top

5 and bottom of the pole, were used to calibrate the temperature measurements along the optical fiber. This DTS system achieved a vertical spatial sampling resolution of 0.4 cm and a temperature resolution of 0.05 °C when 2 min integration intervals were used. Radiative heating on the pole had a profound impact on the air measurements above the glacier (Huwald et al., 2009). In the lake, where the water column was

10 strongly mixed by the presence of waves during overcast conditions, radiative heating of the DTS pole was not observed. As the main purpose of the work performed by Selker et al. (2006) was to demonstrate the potential of DTS methods, only limited efforts were made to quantitatively assess the limitations of their DTS system. For example, having only two points of independent temperature measurements along the DTS

15 pole may result in lower temperature accuracy along the optical fiber than that achieved with longer sections of cable at known temperature. Recently, Vogt et al. (2010) constructed a high-resolution DTS vertical temperature profiler to estimate seepage rates in a losing reach of a river. A fiber-optic cable was wrapped around a 51 mm diameter 1.9 m length PVC piezometer tube. The calibration of their DTS system was performed

20 in the laboratory before field installation with two reference sections at two known temperatures. According to their manufacturer specifications, a temperature resolution of at least 0.11 °C should be achieved for cables shorter than 2 km when 10 min integration intervals were used. Although they were able to study groundwater and surface water interactions, deviations occurred due to calibration and signal noise of the DTS

25 as well as solar radiation heating the DTS pole when the river stage was very low.

With their spatial and temporal resolution, DTS methods offer significant advantages over traditional measurement systems in natural or managed thermohaline environments. Fibers are low cost, with no issues of bias or fluid column disturbance, and can be made completely non-corroding. Radiation effects are similar to traditional sensors

(Neilson et al., 2010). In the following discussion, we demonstrate the utility of this method to accurately monitor temperatures in a strongly stratified aquatic system. A salt-gradient solar pond (hereafter, the term salt-gradient will be dropped) is an engineered shallow thermohaline system that allows collection and storage of solar energy for a long period of time (Suarez et al., 2010b). It consists of three distinct layers: the upper convective zone, the non-convective zone, and the lower convective zone. The upper convective zone is a thin layer of cooler, less salty water. The non-convective zone has gradients in temperature and salinity. The lower convective zone is a layer of high salinity brine where temperatures are the highest. The solar radiation that penetrates the pond's upper layers and reaches the lower convective zone heats the highly concentrated brine, which will not rise beyond the lower convective zone since the effect of salinity on density is greater than the effect of temperature. Because of the steep thermal gradients, and the need to monitor large temperature differences over short distances in time (Suarez et al., 2010a), vertical high-resolution DTS methods may have significant advantages over traditional measurement systems. Nonetheless, DTS methods have complications and limitations that must be understood and assessed in order to achieve improved resolution. For instance, accuracy and precision of DTS systems depend on the fraction of incident light that is backscattered in the optical fiber and thus, one of the main limitations of DTS systems is low signal strength. Hence, care must be taken to avoid signal strength reductions, and evaluation of accuracy and precision of DTS systems is necessary for each installation. Also, DTS systems must be calibrated for differential attenuation of the anti-Stokes and Stokes intensities along the cable as well as instrument sensitivity and drift. Previous DTS investigations in hydrological or environmental applications have never presented the equations that DTS systems use for temperature estimation or temperature calibration. Few investigations in the field of light physics have derived the governing equation for temperature estimation along the fiber (Farahani and Gogolla, 1999; Yilmaz and Karlik, 2006), but their notation is inconsistent and some parameters have not been clearly defined. Therefore, temperature estimation (or calibration) in fiber-optic DTS systems

still remains unclear.

The main objective of this work is to present a method for using DTS technology to obtain more reliable data from vertically wrapped fiber and to assess the limitations of the technology. In particular, this study quantitatively assesses the performance of a vertical high-resolution DTS system, similar to that first presented by Selker et al. (2006), that is being used to monitor temperatures in a shallow thermohaline system. The evaluation of accuracy and precision is described as is a method to manually calibrate the temperatures along the fiber. Here, we made the first attempt to clarify the notation and the definition of the parameters needed to calibrate the temperature along the optical fiber. Temperatures collected with electrical conductivity (EC) probes are used to compare the DTS measurements within the thermohaline environment, and the effect of radiative heating on the optical fiber is also evaluated.

2 Materials and methods

2.1 Vertical high-resolution DTS system

A vertical high-resolution DTS system was constructed consisting of a vertical high-resolution pole, a DTS instrument, two water baths at different temperatures (for calibration purposes), and a fiber-optic cable that connects all the components. The total length of the fiber-optic cable was ~400 m, with ~200 m used in the vertical high-resolution DTS pole, ~50 m used in each bath, and the remainder used to connect the DTS instrument with each component of the system.

2.1.1 Vertical high-resolution DTS pole

A vertical high-resolution DTS pole (Fig. 1a) was constructed by carefully wrapping a duplex multi-mode fiber-optic cable (AFL Telecommunications, Spartanburg, SC) around a 51 mm diameter PVC pipe ~1.3 m in length. The geometric characteristics of

the fiber-optic cable and the PVC pipe allowed 1 m of cable to occupy 1.1 cm of pipe length. The fiber-optic cable consists of a plastic jacket tube with a thixotropic gel and two non-armored optical fibers with core and cladding diameters of 50 and 125 µm, respectively. The cable was secured to the pipe using a white heat-shrink plastic, which also reduced radiative heating. The interior of the PVC pipe was filled with insulating foam to prevent convective heat flow inside the pipe itself. The result was an easily handled, chemically inert, light-weight pole, resistant to the corrosive environment of hot saline water. The two optical fibers were fused at the end of the cable to create a loop of a single cable with both ends connected to the DTS instrument. This allowed access to the entire optical path of the cable via connection of the DTS to either end of the fiber.

2.1.2 DTS instrument

The vertical high-resolution DTS pole was connected to a Sensornet Sentinel DTS (Sensornet Ltd., Herthfordshire, England), which according to the manufacturer, has a temperature resolution <0.01 °C (60 min integration intervals) and a spatial sampling interval of 1.015 m, when cables shorter than 5 km are used. A four-channel multiplexer was employed to allow the use of single- or double-ended measurements. Single-ended measurements refer to temperatures estimated from light transmission in only one direction along the fiber. These measurements provide more precision near the instrument and degrade with distance due to the energy loss along the fiber length. Double-ended measurements refer to temperatures estimated from light transmission in both directions along the fiber. In double-ended measurements, the temperature is estimated using single-ended measurements made from each end of the optical fiber and accounts for spatial variation in the differential attenuation of the anti-Stokes and Stokes signals, which often occurs in damaged or strained fibers. This results in a signal noise more evenly distributed across the entire length of the cable, and uniformly greater than that obtained in a single-ended measurement (Tyler et al., 2009).

Assessment of a DTS system

F. Suárez et al.

2.1.3 Calibration and verification

Here, we present a method to calibrate temperatures along the fibers for single-ended measurements. We recognize that it is also necessary the presentation of a calibration method for double-ended measurements, especially for damaged cables. However, because we did not have damaged or strained fibers and due to the complexity of this method, it is out of the scope of this work and it remains to be a topic that needs to be addressed in future investigations.

The temperature in an optical fiber can be estimated by (Farahani and Gogolla, 1999; Yilmaz and Karlik, 2006):

$$T(z) = \frac{\gamma}{\ln[C] - \ln[R(z)] + \Delta\alpha z} \tag{1}$$

where $T(z)$ is the temperature (K) at a distance z (m) along the fiber; $\gamma = \Delta E/k$ (K), where ΔE represents the difference in molecular energy states that drive Raman scattering and k is the Boltzmann constant; C (–) is a calibration parameter that depends on the wavelength and frequency of the incident laser, the backscattered Raman signals, the instrument's photon detector, and the operating conditions of the DTS instrument; $R(z)=I_{aS}(z)/I_{S}(z)$ (–) is the ratio between the anti-Stokes and Stokes intensities, $I_{aS}(z)$ and $I_{S}(z)$, respectively; and $\Delta\alpha=\alpha_{S}-\alpha_{aS}$ (m^{-1}) is the differential attenuation of the backscattered Stokes and anti-Stokes intensities. Assuming that $\Delta\alpha$ is not spatially dependent, two methods can be used to calibrate the temperatures. First, temperatures can be estimated using the software provided by DTS manufacturers (this is referred to as native-calibrated temperatures). This calibration method assumes that the constant γ is known ahead of time and thus, the calibration requires two points (or sections) of known temperature to determine the constants $\Delta\alpha$ and C. This calibration method has been widely used in previous hydrologic investigations (Selker et al., 2006; Westhoff et al., 2007; Tyler et al., 2009). Second, temperatures can be calibrated manually using Eq. (1). This calibration method assumes that the constants $\Delta\alpha$, γ and C are not known ahead of time. As a result, this calibration method requires three points

(or sections) of known temperature. Two of these points can be at the same temperature and the other one at a different temperature. In the manual calibration method, two points held at the same temperature on the optical fiber are used to calculate $\Delta\alpha$. If z_1 and z_2 are the positions of these points, Eq. (1) yields:

$$\Delta\alpha = \frac{(\ln[R(z_1)] - \ln[R(z_2)])}{(z_1 - z_2)} \tag{2}$$

Once $\Delta\alpha$ is known, the values of C and γ are calculated using Eq. (1) at two points on the fiber held at different temperatures:

$$\ln[C] = \frac{(\ln[R(z_1)] - \Delta\alpha z_1)T(z_1) - (\ln[R(z_3)] - \Delta\alpha z_3)T(z_3)}{T(z_1) - T(z_3)} \tag{3}$$

$$\gamma = (\ln[C] - \ln[R(z_1)] + \Delta\alpha z_1)T(z_1) \tag{4}$$

where z_3 is the position of a point on the fiber that has different temperature than that at positions z_1 or z_2. After the values of $\Delta\alpha$, C and γ are known, Eq. (1) is used to calculate the temperatures along the entire fiber. Calibration parameters ($\Delta\alpha$, C and γ) are recalculated for each time-step and are assumed to be uniform over the entire fiber length.

Two water baths were used as known-temperature reference sections to calibrate and verify the temperature readings of the DTS system (Fig. 1b). The first 25 m of cable were placed in a room-temperature water bath (cold bath) and were used to calibrate the temperature along the fiber. A four-wire 100-Ohm platinum resistance thermistor (PT100, ±0.1 °C) was positioned in the cold bath. The next 25 m of cable were placed in a microprocessor-controlled water bath (Precision 280, Thermo Electron Corporation, Waltham, MA) at a constant temperature of ~60 °C (hot bath). A second PT100 thermistor (±0.1 °C) was placed in the hot bath to verify the calibrated DTS readings. Air was circulated in both water baths to insure well mixed, isothermal conditions. The PT100 thermistors were previously calibrated using an NIST-traceable VWR thermometer (±0.05 °C; Control Company, Friendswood, TX).

2.1.4 Resolution and repeatability

Spatial resolution is typically defined by DTS manufacturers as the length of cable required to show 80% of the temperature change between two known temperatures. To evaluate the spatial resolution of the DTS system, the step change in temperature
5 between the cold and hot baths was analyzed. To evaluate the temporal resolution, a location on the optical fiber was monitored. When a fast and significant change in temperature occurred, the response time of the system was recorded and the temporal resolution was determined.

Repeatability refers to the agreements between successive measurements carried
10 out under the same conditions. Spatial repeatability was quantified during a single trace by the standard deviation of consecutive temperature measurements over a given length of fiber that is at uniform temperature (Tyler et al., 2009). Temporal repeatability was quantified in a single point of the trace that was at a constant temperature by calculating the standard deviation of consecutive temperature measurements over a given
15 time period.

2.1.5 Single- and double-ended measurements

The effect of single- and double-ended measurements on the temperature measurements was evaluated by comparing the temperature readings in the hot bath. In addition, the effect of temporal integration was also studied. Different combinations of
20 measurements (single- and double-ended) and integration times were evaluated.

2.2 Evaluation of the vertical high-resolution DTS system in an experimental solar pond

A laboratory-scale experimental solar pond (Fig. 1c) was used to test the vertical high-resolution DTS system. To mimic the sunlight spectrum, three high-intensity-discharge

lamps were installed over the pond. Each lamp consists of a 1000 W dual arc tube with two simultaneously operating arc tubes of metal halide and high pressure sodium. Net radiation was measured ∼10 cm above the water surface using a net radiometer (Q-7.1, Campbell Sci., Logan, UT). Incoming and reflected shortwave radiation were

5 also measured ∼10 cm above the water surface using two pyranometers (LP02, Hukse-flux, Delft, The Netherlands). These data were collected using a datalogger (CR23X, Campbell Sci., Logan, UT) at 5 min intervals. Temperature and EC within the water were measured at ten points using EC electrodes (SK23T, Van London-pHoenix Company, Houston, TX) with automatic temperature compensation. Nine of the electrodes

10 were made of glass and one of epoxy. The epoxy electrode replaced a glass electrode that broke during installation. A modular multi-channel datalogger (D230, Consort, Turnhout, Belgium) was used to record the data from the EC electrodes at 5 min intervals.

The lower 50 cm of the solar pond (i.e., the lower convective zone) was filled with

15 a 20 wt% sodium chloride (NaCl) solution. Then, eight layers of successively lower concentrations were added up to an elevation of 90 cm measured from the bottom of the solar pond (i.e., the non-convective zone). The final layer (i.e., the upper convective zone) was filled with tap water. The average water level in the solar pond was 101 cm (measured from the bottom), but the actual level varied from 98 to 103 cm due

20 to evaporation and freshwater resupply. The average water level was used to calculate depths within the solar pond throughout the experiment (regardless that the true water level varied). The solar pond was covered tightly and allowed to sit for three days after filling. Then, the pond was exposed to the artificial lights 12 h per day and its thermal response was monitored.

25 In a separate investigation to assess the impact of radiative heating on the DTS pole, the lights over the pond were operated continuously. When the solar pond was close to thermal steady state, the DTS pole was shaded using a white expanded-foam PVC shield (Fig. 1a). Holes were made in the shield to allow air and water to move across it. The DTS pole was covered for approximately 60 min until a new steady state was

Assessment of a DTS system

F. Suárez et al.

reached. After this, the DTS pole was uncovered and temperatures were recorded until the initial value was reached.

3   Results and discussions

3.1   Vertical high-resolution DTS system

Typical Raman-scattering and temperature traces obtained during the experiment are presented in Fig. 2. Figure 2a shows the scattered anti-Stokes and Stokes signals along the fiber optic cable, the location of the components of the system (cold and hot bath, vertical high-resolution DTS pole), and the location of the distinct layers inside the solar pond. Figure 2b shows typical calibrated-temperature traces obtained during the experiment, and the locations where the cable was fused. The temperature traces are symmetrical because the two fibers within the cable were fused at the end (fusion splice 2) to create a single loop. Figure 2 also shows how the temperature along the optical fiber affects the anti-Stokes and Stokes signals. As expected, the anti-Stokes signal is strongly dependent on the temperature along the fiber while the Stokes signal is weakly dependent on the temperature.

3.1.1   Calibration and verification

Figure 3a shows a comparison of the temperatures measured in the cold bath by the PT100 and by the DTS system. The DTS temperatures were calibrated using the software provided by the manufacturer (i.e., native-calibrated temperatures). These temperatures are expected to be the same because the DTS instrument uses the temperature measured in the cold-bath PT100 to correct the temperature measurements along the entire optical fiber. A normal probability plot (inset of Fig. 3a) shows that the difference between the DTS and PT100 temperatures follows a standard normal distribution (i.e., $\sim N(0, 1)$). Thus, these temperature differences are verified to be independent and could be considered as random noise with 95% confidence (Box et al., 2008).

The native-calibrated DTS readings were verified by comparing the DTS and the PT100 measurements in the hot bath, as shown in Fig. 3b. The temperatures of both instruments are in agreement, although their differences have more variability than those measured in the cold bath. However, a normal probability plot shows that these temperature differences are also $\sim N(0,1)$. Thus, random noise in the DTS system is the main reason for the observed differences, with a 5% significance level (Box et al., 2008). Statistically, the DTS and the thermistor measure the same temperature, verifying the readings of the DTS system.

To illustrate the manual calibration method, single-ended traces of the anti-Stokes and Stokes intensities were used to estimate the temperatures along the optical fiber. These temperatures were compared to native-calibrated temperatures. The $\Delta\alpha$ was calculated from two sections on the optical fiber held at the same temperature ($z_1 = 10$–25 m and $z_2 = 370$–385 m, in the cold bath at $\sim$19.6 °C, as shown in Fig. 2). The values of C and γ were calculated from two sections on the fiber held at different temperatures ($z_1 = 10$–25 m at $\sim$19.6 °C in the cold bath and $z_3 = 340$–355 m at $\sim$61.5 °C in the hot bath). Figure 3c compares native- and manually calibrated temperatures within the solar pond. Generally, these calibrated temperatures differ in less than 0.1 °C in the solar pond. The root mean square error (RMSE) of the points of known temperature along the cable was used to determine the goodness of the agreement between these calibrations. The manually calibrated temperatures (RMSE = 0.05 °C) are closer than the native-calibrated temperatures (RMSE = 0.25 °C) to the independent measures of temperature of the baths. This occurred because native-calibrated temperatures were estimated by varying two calibration parameters ($\Delta\alpha$ and C), while in the manual-calibrated temperatures three calibration parameters ($\Delta\alpha$, C and γ) were allowed to vary. Thus, manual post-processed data resulted in a more robust and usable data set.

3.1.2 Resolution and repeatability

The spatial resolution was evaluated using the step change in temperature between the cold and hot baths. Utilizing 15 days of data (4495 temperature traces), it was found that the mean spatial resolution of the DTS system was 2.056 ± 0.047 m, which
5 is twice that reported by the manufacturer. Note, however, that spatial resolution could also depend on the fiber-optic cable or other factors (e.g., connectors, testing methodology, cable layout). The results obtained here and in a previous study (Tyler et al., 2009) suggest that spatial resolution is at least two times the sampling resolution of the instrument. The temporal resolution of the high-resolution DTS pole was evaluated
10 at ~1 cm above the air-water interface. An integration time of 10 s was utilized. Before the lights were turned on, a constant temperature of $24.223 \pm 0.096\,°C$ was monitored. After the lights were turned on, a significant and fast change in temperature ($>4\,°C$ in less than 5 min) was observed. The DTS system took less than 40 s to register an increase in temperature larger than $2\sigma = 0.192\,°C$. Thus, the temporal resolution of the
15 DTS system was ~40 s with 95% confidence.

Spatial repeatability was quantified during a single trace in the hot bath. The average temperature was $61.429 \pm 0.014\,°C$. This is a very good spatial repeatability that is much better than that obtained in previously reported DTS experiments (Tyler et al., 2008, 2009). Temporal repeatability was also evaluated in the hot bath. The PT100
20 reported an average temperature of $61.333 \pm 0.120\,°C$, while that reported by DTS system was $61.410 \pm 0.121\,°C$. This suggests that actual variability of the hot bath controls the repeatability of the DTS measurement.

3.1.3 Single- and double-ended measurements

As shown in Table 1, as the integration time increases the standard deviations of
25 both single- and double-ended measurements decrease. For all the integration times, single-ended measurements show smaller standard deviation than double-ended measurements. An integration time of 300 s showed spatial repeatability (standard

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

deviations) of 0.035 and 0.055 °C in the hot bath for single- and double-ended measurements, respectively. This integration time was long enough to provide good temperature resolution and short enough to monitor the transient phenomena and the physics of solar ponds. These results show that the DTS system is able to resolve
5   temperatures with very small variability using both types of measurements. In this experiment the cables were less than one tenth the instrument's range, so noise levels were roughly the same in single- and double-ended measurements for equivalent integration times. Somewhat surprisingly, the expected decrease in standard deviation with the square-root of the integration time did not hold for the double-ended measure-
10 ments, which showed less than half the expected improvement in precision, while the single ended measurements achieved about 70% of the theoretically anticipated improvement. A frequency stability analysis, using the modified Allan variance method (Rubiola, 2005), showed the presence of a combination of white and flicker noises. Flicker noise (also known as $1/f$ or pink noise) is ubiquitous in physics (Lawrence
15 et al., 1987; Kaulakys and Alaburda, 2009) and is expected in technologies that use weak optical signals such as Raman-scattering applications (McDowell et al., 2008). When white and flicker noise are combined, the signal-to-noise ratio of optical instruments is smaller than that obtained when only white noise is present. As a result, the expected decrease in standard deviation due to increasing averaging time is also
20 smaller.

3.2 Evaluation of the vertical high-resolution DTS system in an experimental solar pond

The thermal evolution of the water column and the air above it is presented in Fig. 4a. The night surface cooling, the non-convective zone stratification, and the warming
25 of the lower convective zone are observed at high spatial and temporal resolutions. To the best of our knowledge, this is the first time that temperatures have been reported at such high spatial and temporal resolution in solar ponds (Lu et al., 2004; Kurt and Ozkaymak, 2006). This spatial and temporal resolution of the temperature

observations is not only a tool for monitoring temperatures at near real-time but also could become a tool for decision-making. For instance, at the beginning of the experiment, no water was added to the surface of the pond and evaporation decreased the water level. After one week, the DTS system showed air temperatures at more than
5 5 cm depth; for this reason it was decided to resupply freshwater at the surface of the pond. The timing of the first resupply is clearly observed in Fig. 4a. The DTS system could also be used to automatically and remotely control the operation of a solar pond. For example, if the temperature of the lower convective zone is sufficiently high to generate useful heat, the DTS system could trigger heat extraction, reducing the tem-
10 perature in this zone and providing low grade heat for other processes on site. On the other hand, if the temperatures in the bottom of the pond are too low, the DTS system can stop the heat extraction until an acceptable temperature threshold is reached.

Figure 4b shows the thermal evolution at different depths within the solar pond. When comparing the red and black lines, it can be seen that during the first days
15 of the experiment, the upper convective zone is stratified during the day and completely mixed during the night (due to penetrative convective mixing). After one week, the upper convective zone is always completely mixed. This occurred mainly because a higher temperature in the non-convective zone induces thermal convection cells in the upper convective zone; also, it could have been a result of turbulent mixing when fresh-
20 water was resupplied at the surface of the pond at days 6, 8, 9, 10, and 13. Figure 4b also shows that the non-convective zone strongly stratifies and that temperatures in the middle of this zone (orange and gold lines) are less affected by daily fluctuations. The close-up in Fig. 4b shows that the lower convective zone is completely mixed during the day because of radiation absorption at the bottom of the pond but stratified at night be-
25 cause heat is lost through the non-convective zone as well as through the bottom and sides of the experimental solar pond. These heat losses can be easily assessed using the DTS system (e.g., by evaluating the thermal gradient measured near the bottom).

Figure 5 shows the temperature profiles using the DTS system and using EC probes for different days of the experiment. The initial design of the experiment located the

interface between the non-convective and the lower convective zones at 0.5 m depth. On the morning of 6 March 2009, only the lower convective zone of the solar pond was filled. At this time, the temperature profile measured with the DTS system showed an essentially uniform water temperature below the air boundary layer that begins at the water surface. The spatial resolution obtained with the vertical high-resolution DTS system cannot be readily achieved with a fixed array of thermocouples; or by using a DTS system with a linear arrangement of the fiber. The DTS method was also found to be less affected by the aggressive saline environment. For instance, on the morning of 6 March, though the EC probes showed the same spatial trend as the DTS system, the submerged EC probes exhibited higher temperatures than those measured by the vertical high-resolution DTS system. On the other hand, the EC probes above the water surface confirmed that the air temperature measured with the DTS pole was properly reported by the DTS instrument. It appears that the brine caused an offset of ~0.5 °C in the submerged EC probes. Electrode drift due to the saline environment (Bergman et al., 1985) could have been one of the reasons for this offset. The EC probe located at ~0.4 m depth, which was the single probe made of epoxy, consistently reported lower temperatures than the other probes. This clearly demonstrates the disadvantage of data scatter due to biases between sensors when using a fixed array. In addition, the EC probe located at ~0.75 m depth did not record both temperature and EC throughout the experiment.

The filling of the non-convective zone started at 10:30 a.m. the morning of 6 March 2009. When the first layer of this zone was poured over the lower convective zone, turbulent mixing was observed. Therefore, an unwanted reduction of the lower convective zone was expected. The filling of the pond was completed the afternoon of 6 March and the pond was tightly covered to avoid heat transfer between the water and the ambient air. On 9 March, the pond was left uncovered during the night and the experiments started at 09:00 a.m. the morning of 10 March. At 08:54 a.m. (6 min before turning on the lights for the first time), the effect of surface cooling at night is clearly visible in both the DTS system and the EC probes (yellow data in Fig. 5). By 13 March, the

Assessment of a DTS system

F. Suárez et al.
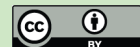
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Interactive Discussion

DTS system already shows that the lower convective zone is completely mixed. Furthermore, the vertical high-resolution DTS system shows that the interface between the non-convective and lower convective zones is located deeper than the desired level (at ~0.65 m depth), confirming the unwanted reduction of the lower convective zone due to turbulent mixing. If the temperatures measured with the EC probes are analyzed, the lower convective zone is not as clear as in the DTS measurements because almost all the data points along the water column are scattered between 23 and 24 °C (without considering the probe located at ~0.4 m depth). On 25 March, the DTS system shows that the temperature profile in the non-convective zone corresponds with the theoretical profile expected when a static fluid is absorbing energy, i.e., a non-linear gradient occurs when conduction is the main heat transfer mechanism and radiation produces internal heating of the fluid (Bejan, 2004). The temperatures measured by the EC probes show a slight curvature in the non-convective zone, but it is not clear if it is a constant temperature gradient or not. In Fig. 5, the gray-dashed line shows erosion of the lower convective zone observed using the DTS system. On 25 March, the DTS system shows the location of the interface between the non-convective and lower convective zones at ~0.7 m depth. Because of the poor spatial distribution of the EC probes, these sensors show the interface between the non-convective and lower convective zone at ~0.6 m depth. This erosion of the lower convective zone is likely due to salt diffusion and it is important to quantify it to correctly predict the efficiency of solar ponds (Suarez et al., 2010a).

The results of the radiative heating experiment are presented in Fig. 6. The temperatures measured by the DTS system in the air above the water column and the temperatures in the upper convective zone were the ones most affected by radiation absorption, while the water temperatures below the upper convective zone were not affected when the DTS pole was shaded. As shown in Fig. 6a, after 20 min of covering the DTS pole, the temperature readings at 2.3 cm above the water level achieved a new steady-state. Here, the temperature readings were 0.7 °C lower than those without the cover. Figure 6b shows the thermal profiles measured with the DTS system for different

times during the radiative heating experiment. When the DTS pole was covered, the air temperature profile changed from a non-linear shape into a more linear shape. This is expected in a static system that is not subject to internal heat generation (Bejan, 2004). Thus, when the DTS pole is not shielded, the curvature observed in the air temperature
5 profile is due to absorption of radiation in the DTS pole. In the upper convective zone, the temperature decreased by ~0.1 °C when the DTS pole was shielded. When the shield was removed, the temperature of this zone increased rapidly for the first 15 min until a new steady state was reached at the end of the experiment, demonstrating how radiation absorption in the DTS pole affects the temperature measurements at shallow
10 depths.

Radiative heating of the DTS pole, for the radiation levels tested here (243 W m^{-2} at the water surface – limited by the intensity of the artificial lights), was significant only when air or shallow water were measured. Temperature measurements with the DTS pole between the water surface and 10 cm depth showed only an additional 0.1 °C
15 that was attributed to radiation absorption. Peaks of natural solar radiation can be 3–4 times higher than the radiation levels tested here. Hence, the impact of solar radiation absorption on the DTS pole, as well as on other temperature sensors that are not shielded, may be important when water temperatures are being measured. The systems may be especially sensitive when water velocities are very small, i.e.,
20 when conduction is the dominant heat transfer mechanism, and when the magnitude of solar radiation is large and zenith angles are small, i.e., close to solar noon (Huwald et al., 2009; Neilson et al., 2010). The impact of solar radiation absorption on fiber-optic cables can be reduced using reflective coatings or using shields to shade the cables. An optimal shield should minimize the radiation reaching the cable and the
25 radiation absorbed by the shield, while maximizing the air or water flow around the cable (Richardson et al., 1999). If reflective coatings are used, care must be taken to not affect, i.e., warm, the surrounding environment (e.g., see Huwald et al., 2009).

4 Summary and conclusions

As temperature is a major driver of changes in natural and managed systems, there is a need to observe temperatures at high spatial and temporal resolutions. The vertical high-resolution DTS system provides a reliable method to monitor temperature in space and time, which is essential not only in understanding the physics of solar ponds or other thermohaline environments but of the majority of shallow water bodies. Processes such as penetration, absorption or scattering of light in aquatic system, and their temporal fluctuations, can be well addressed with the high-resolution DTS system. In addition, the present DTS system overcomes the problems typical of methods used in the past such as drift due to corrosive environment. This is a major issue in thermohaline systems, particularly in solar ponds where the salinity approaches saturation.

This paper presented a methodology for calibration as well as for evaluation of spatial and temporal repeatability and resolution that helps to maximize the potential of the fiber-optic DTS technology for hydrologic applications. The present DTS system monitored the temperature profile in a solar pond each 1.1 cm vertically and in time averages as small as 10 s. Temperature resolution as low as 0.035 °C was obtained when the data were collected at 5 min intervals. It was found that the DTS system resolved temperatures with very small variability using either single- or double-ended measurements, and that the observed noise in the system could be due to a combination of white and flicker noise. Using the vertical high-resolution DTS system, stratification, mixing, interface erosion, and freshwater resupply were observed in the solar pond at a resolution that is hardly achievable using traditional temperature sensors. Radiation absorption was found to be significant only when air or shallow water temperatures were measured. However, it may be important in systems exposed to natural solar radiation.

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion
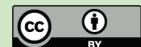
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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 1. Comparison between single-ended (SE) and double-ended (DE) measurements in the hot bath. T is average temperature and σ is standard deviation.

Integration time (s)	T_{SE} (°C)	σ_{SE} (°C)	T_{DE} (°C)	σ_{DE} (°C)
20	61.419	0.103	61.322	0.112
120	61.612	0.046	61.321	0.069
300	61.618	0.035	61.261	0.055

Full Screen / Esc

Printer-friendly Version

Interactive Discussion
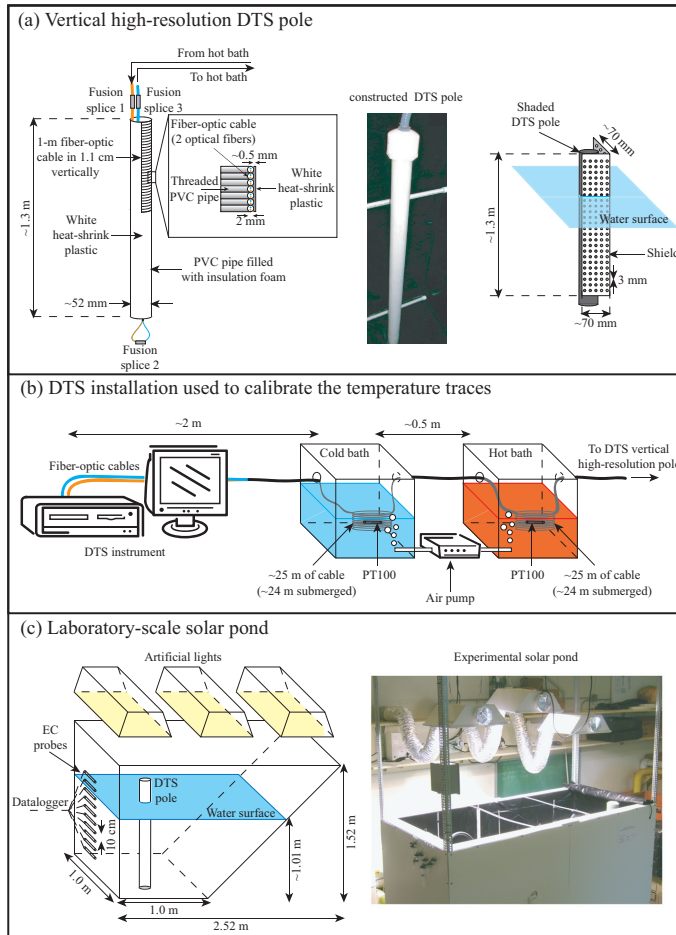
Fig. 1. Diagrams of the **(a)** DTS pole, **(b)** DTS installation, and **(c)** experimental solar pond.
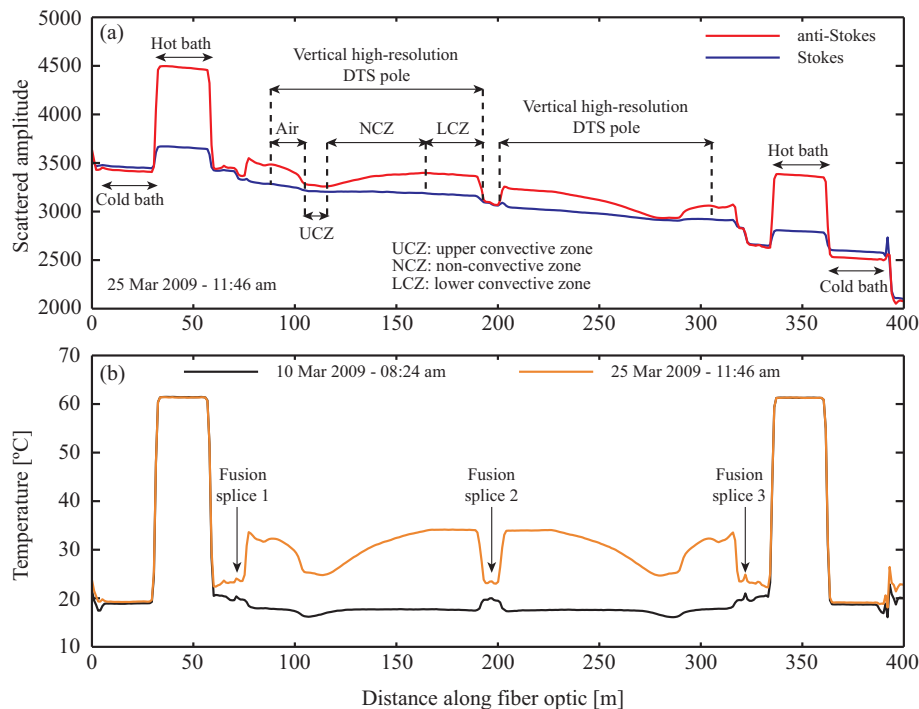
Fig. 2. **(a)** Typical Raman-scattering traces obtained during the experiment show the impact of temperature on the anti-Stokes and Stokes signals. Locations of the system components (cold and hot baths, vertical high-resolution DTS pole) are also shown. **(b)** Typical temperature traces obtained during the experiment. The black line was obtained at the beginning of the experiment and the orange line was obtained after 15 days.

Title Page

Abstract | Introduction

Conclusions | References
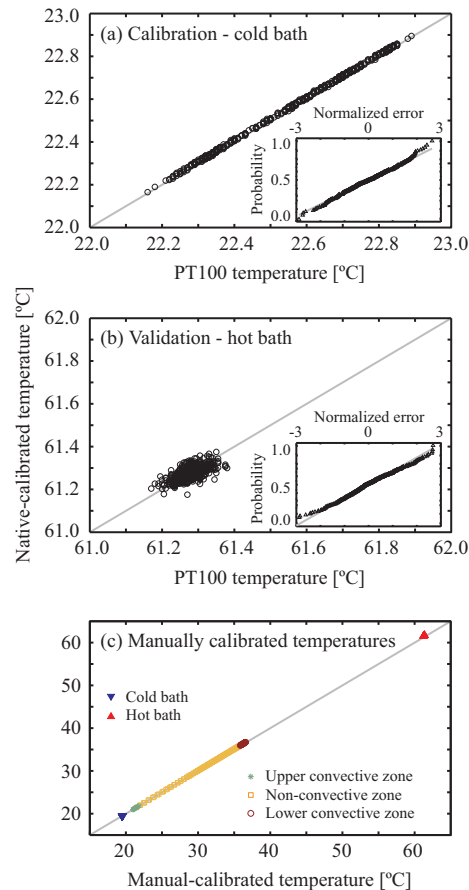
Tables | Figures

◄◄ | ►►

◄ | ►

Back | Close

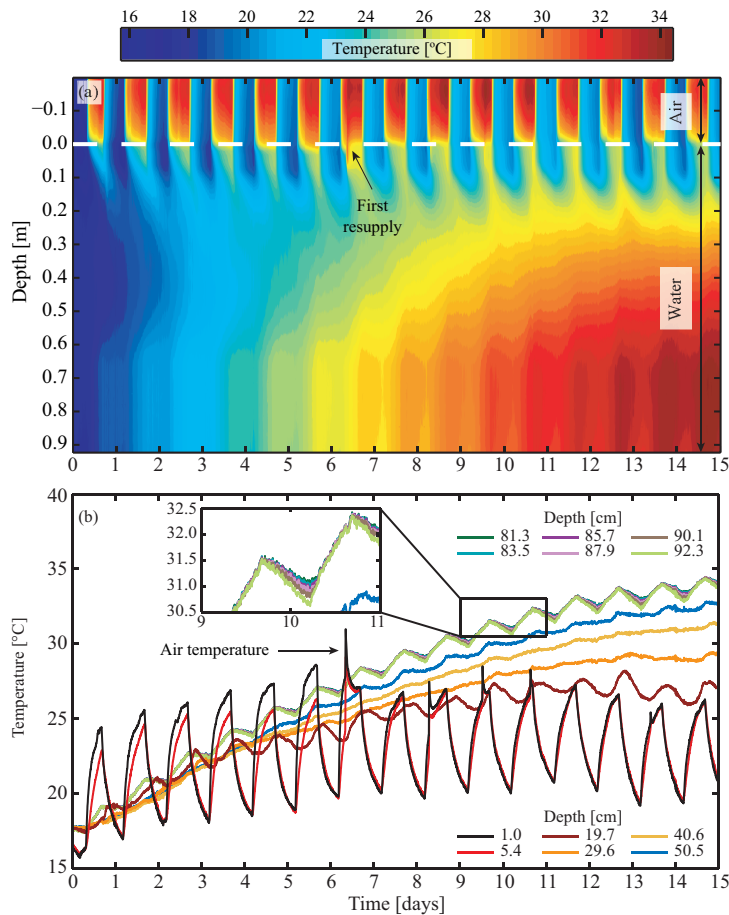Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Fig. 3. (a) The DTS system is calibrated by comparing the PT100 temperature measurements with the DTS native-calibrated temperatures in the cold bath. **(b)** The DTS system is validated in the hot bath. **(c)** Manual- and native-calibrated temperatures are compared.

Fig. 4. (a) Thermal evolution of the water column and the air above it collected with the vertical high-resolution DTS system. **(b)** Time series of temperature at specific depths inside the solar pond.
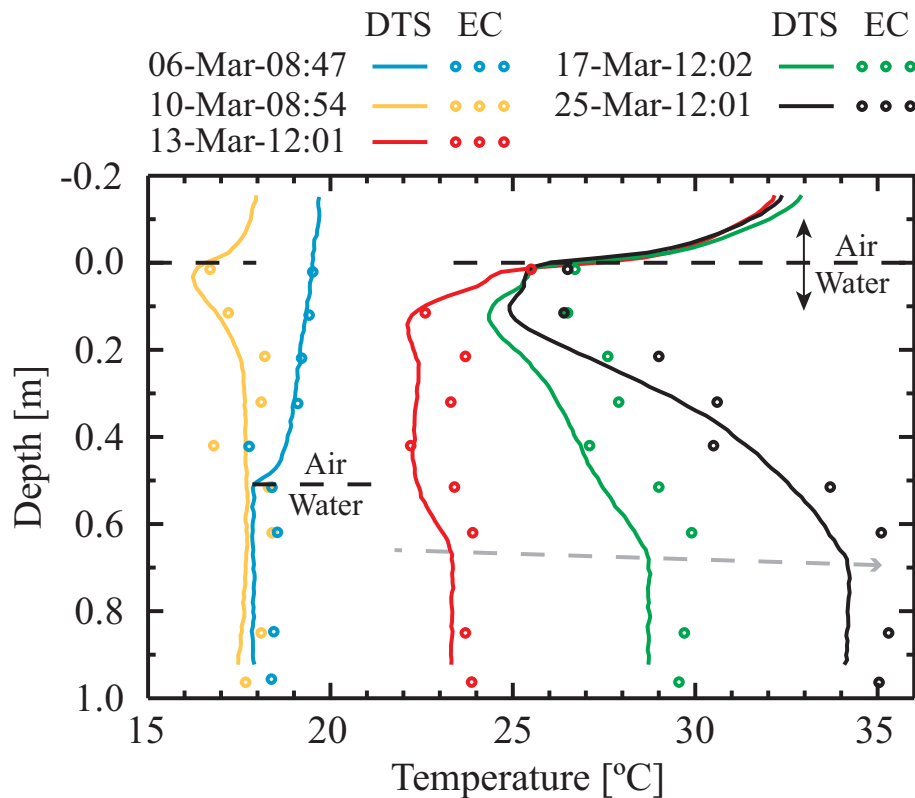
Fig. 5. Comparison of the temperature profile measured with the DTS system and with electrical conductivity (EC) probes. In the morning of 6 March the solar pond was filled to a depth of 0.50 m.

Title Page

Abstract | Introduction

Conclusions | References
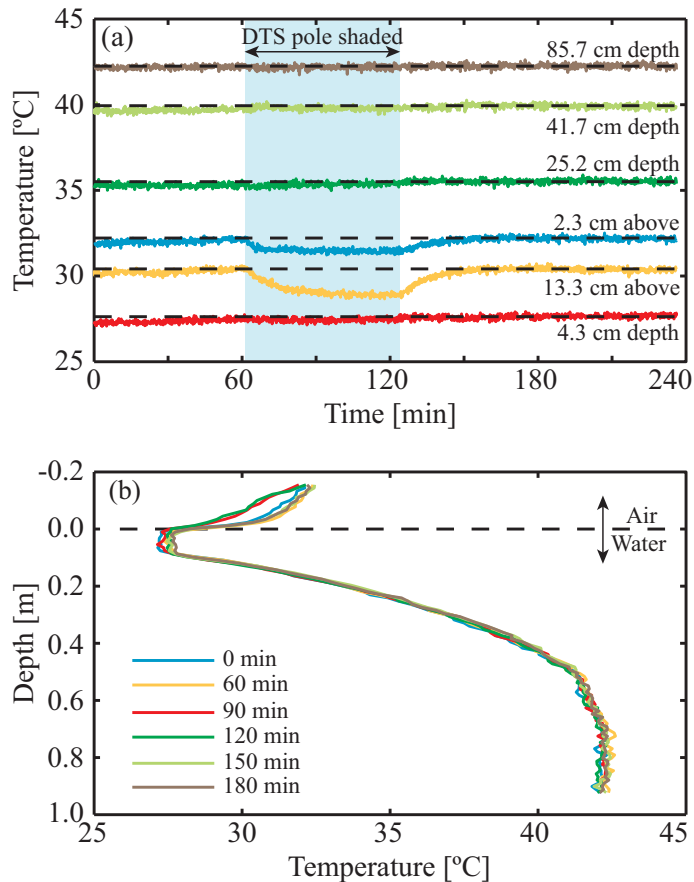
Tables | Figures

◄◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Fig. 6. Assessment of radiative heating of the DTS pole. **(a)** Thermal evolution at different depths in the water column and in the air. **(b)** Temperature profile measured with the DTS system at different times of the experiment.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

HESSD

8, 29–58, 2011

Assessment of a DTS system

F. Suárez et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion