As promised, we now individually address the comments received from Dr. Westhoff. Note that the Referee's comments were **bolded** and our responses maintained the regular font format.

General comments: This manuscript presents a method to, in their words, "manually calibrate temperatures along an optical fiber". Since this measuring technique is more and more used in hydrology it is of high relevance and therefore potentially worth publishing.

As explained before, the manuscript is not only limited to a manual calibration of the temperatures along the optical fiber. We have modified the manuscript to be more clear in the objectives of this work:

"The main objectives of this work are to present a method for using DTS technology to obtain more reliable temperature data 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 and the selection between single- and double-ended measurements (described below) is discussed. A new method to manually calibrate the temperatures along the fiber is presented, and the notation and definition of the parameters needed to calibrate the temperature along the optical fiber is clarified. Although this study focuses on vertically wrapped fibers, the assessment presented here is also valid for DTS systems with linear arrangement of the fiber. A second objective is to demonstrate the utility of this method to accurately monitor temperatures in a salt-gradient solar pond (hereafter, the term salt-gradient will be dropped), an engineered shallow thermohaline system that consists of three distinctive layers (Suárez et al., 2010b): the upper convective zone, a thin layer of cooler, less salty water; the non-convective zone, which has gradients in temperature and salinity; and the lower convective zone, a layer of high salinity brine (near saturation) where temperatures are the highest. In particular, temperatures collected with electrical conductivity (EC) probes are used to compare the DTS measurements within the solar pond, and the effects of radiative heating on the optical fiber are evaluated."

However, there are a couple of things that need more attention:

Especially the calibration and verification (section 2.1.3) should be better explained since this is the main objective of the paper. I miss an exact explanation of the method the DTS software uses and I had problem in understanding which known temperatures are used during which step. Since others may want to reproduce this exactly, when calibrating their measurements, I suggest writing each step of the calibration procedure, without leaving gaps or room for misinterpretations.

We apologize for the misunderstood about the main objective of the paper. Also, as explained in our previous general response, we cannot provide an exact explanation of the method that manufacturer's DTS software uses (now referred to as manufacturer-internal calibration method) to calibrate the temperature along the fiber optic. These methods and algorithms are generally proprietary information that DTS manufacturers do not give to their users. In addition, DTS instrumentation typically has an extensive explanation of the steps needed to calibrate the temperature using their manufacturer-internal calibration. That being said, we do provide details of calibrations based upon the theoretical and published response of the scattered Raman spectral signals and we have tried to clarify the steps in our new calibration method (now referred to as extended calibration). In the responses below we have described how we modified the manuscript to address this comment.

A lot of attention is given in describing and explaining the temperature gradients in the solar pond (already in the introduction). However, it is 'just' a case study to demonstrate the calibration procedure and to show the advantage of DTS measurements above classical temperature observation techniques. It is outside the scope of this paper to explain in detail how and why the different temperature layers behave the way they do. See the specific comments which parts I suggest to shorten or eliminated.

As explained before, we agree with Dr. Westhoff that we were excessively detailed to describe the physics observed inside the solar pond. We have modified the final manuscript removing many sections that were interpretation of the data obtained. Also, we maintained some sections that we believe are important because they show important features observed with the vertical high-resolution DTS system that are hard to observe using more traditional moderate-cost sensors or DTS systems with a linear arrangement of the fiber. In the responses below, we clearly describe what we have modified in the manuscript to address this comment.

My third general comment is that I miss a short sensitivity analysis: what happens when z1 and z3 are switched, or when T(z1) is the average of only 10m etc. These are things that can be done with the same dataset.

We greatly appreciate this comment of the Referee. We agree with that a short sensitivity analysis was needed. We have performed this analysis (see responses below).

Specific comments:

Abstract: first describe the objective of the paper (as in line 13-16) before describing the case study. Emphasize that native and manual calibration methods are presented.

We have revised our abstract according to the objectives of the work:

"<u>Abstract</u>

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 paper describes a method to quantitatively assess accuracy, precision and other limitations of DTS systems to fully utilize the capacity of this technology, with a focus on vertical high-resolution to measure temperatures in shallow thermohaline environments. It also presents a new method to manually calibrate temperatures along the optical fiber achieving significant improved resolution. 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. The vertical high-resolution DTS 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."

Introduction:

General: Keep a little bit broader scope in the first two paragraphs. Don't focus too much on the solar pond yet, but give more examples of the use of temperature in hydrology, such as vertical upwelling or downwelling water (see for example Constantz 2008). Clearly point out which studies used DTS and indicate what is lacking in their study to prepare the reader for the objective of this study.

While we understand the concern of the Referee we want to point out that our main focus was to develop a reliable method to monitor temperatures in shallow water bodies. Thus, our introduction was written focusing on these environments and specifically in DTS work previously done using vertically wrapped poles (Selker et al., 2006; Vogt et al., 2010), in which we clearly explained their limitations.

P31 L18-23: This part should be in the methods sections

Please note that this is a general description of how DTS systems work. This is the reason why we decided to include it here.

P32 L1-11: Shorten this part. Leave out all the detail and only tell that they wrapped a cable around a pole to obtain higher spatial resolution, and that radiative heating influenced the measurements

Please see response to comment P33 L17-23 (below). Thanks

P32 L16-25: Same as previous comment: skip all the details.

Please see response to comment P33 L17-23 (below). Thanks

P33 L3-14: Leave out. Just describe the case study briefly after the objective.

Thanks for this comment. We have described shortly the solar pond and its configuration after our objectives.

P33 L13-17: Eliminate: you have pointed out the need for higher spatial resolution before.

Corrected.

P33 L17-23: Again: don't go too much in detail, but describe in the methods section instead.

Please note that in P32 L1-25 and in P33 L13-L29 we are describing and indicating what is lacking in previous studies. We are preparing the reader for the objective of this investigation.

P33 L23-29: Indeed, this is part of the problem!

P34 L3: skip "vertically wrapped". The objective is also valid for non-wrapped cables.

We have corrected this (in the first response we have described how we changed the manuscript to address this comment).

P34 L10-13: add a short description of the case study.

We have corrected this (in the first response we have described how we changed the manuscript to address this comment).

P34 L21: I suggest combining section 2.1.1, 2.1.2 and 2.2 and calling it 'Experimental setup'

While we understand the suggestion of the reviewer, we believe that combining these sections into one section could be more confusing. Currently, the methods section is divided into two main subsections: 2.1 Vertical high-resolution DTS system and 2.2 Evaluation of the vertical high-resolution DTS system in an experimental solar pond. Section 2.1 (and 3.1) deals with the DTS system excluding the solar pond, and section 2.2 (and 3.2) brings together the DTS system analyzed before with the solar pond.

P34 L23: Does this mean that there are 2 fibers in 1 cable?

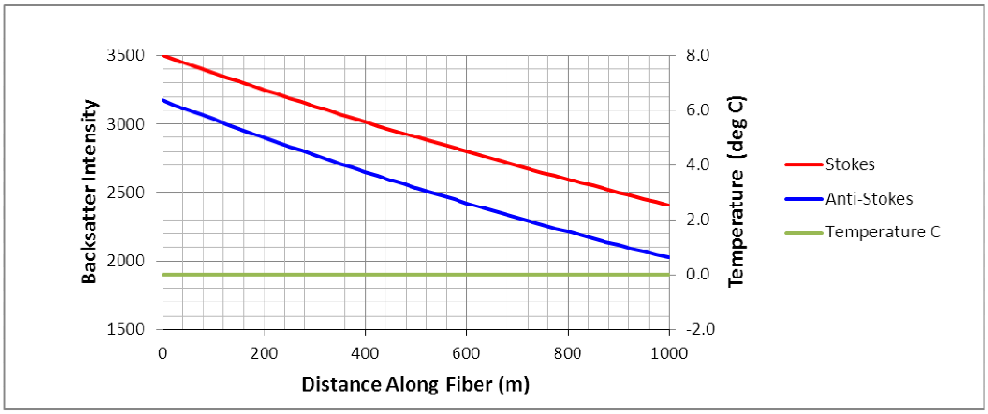
Yes, a duplex fiber-optic cable has two fibers inside. In the revised version of the manuscript we have added "(i.e., two fibers in one cable)" after "duplex" to clarify this term.

P36 L1: If you only used the single ended measurements, why did you employ a multiplexer?

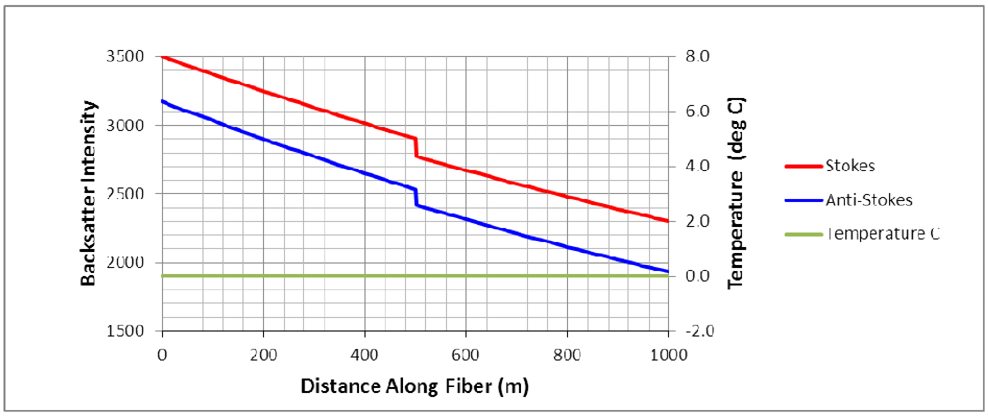
We employed a multiplexer because our DTS unit has this multiplexer incorporated into the unit (which we cannot remove). Please also note that both single- and double-ended measurements were presented in the manuscript.

P36 L5: 'we did not have damaged or strained fibers': There are a couple of splices in the cable that have an effect on the signal

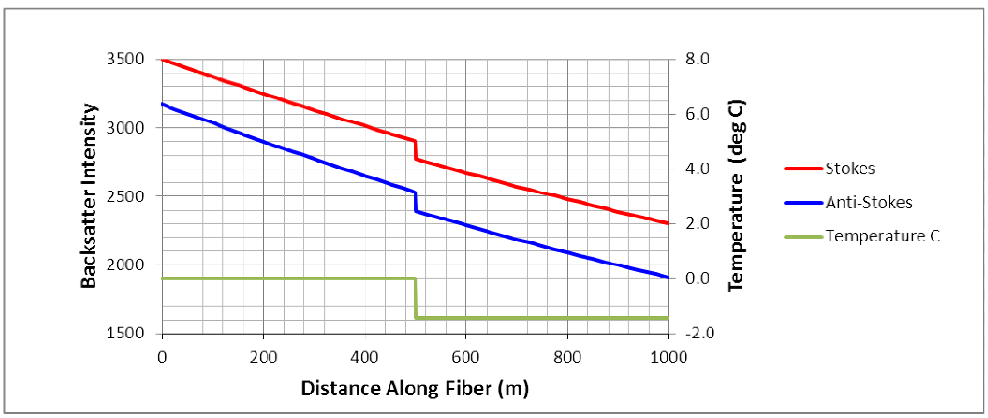
Thanks for pointing this out. We do have 3 splices that resulted in small step losses on the signals (as shown in Figure 2a in the manuscript). However, note that changes in differential attenuation result in anomalies in the temperature estimation along the optical fiber. To show this, in supplementary Figure 1 (below), we have assumed a fiber that is at a constant temperature of 0 °C. If no step losses occur along the cable, the temperature can be correctly estimated using our approach (Supplementary Figure 1a). If a step loss occurs at 500 m $\leq z \leq$ 501 m, and the differential attenuation does not change (Supplementary Figure 1b), the temperature along the fiber again is correctly estimated. However, if the differential attenuation changed in the step loss (Supplementary Figure 1c), the temperature is not estimated correctly and a temperature offset occurs. In our data, the change in differential attenuation after the step losses was negligible; therefore, the effect of the splices in the signal does not induce a significant error. Please note that we are currently trying to expand existing calibration methods for environmental applications (including for strained/damaged fibers in which differential attenuation changes along the cable) and we respectfully request not to give details about this complex method in this paper and leave this for future work.



(a)



(b)



(c)

Supplementary Figure 1. Effect of a step loss (located between 500 and 501 m) in the temperature estimation along an optical fiber that is at a uniform temperature of 0 °C. (a) No step loss. (b) Assuming an equal step loss of 0.2 dB/m in the Stokes and anti-Stokes signals, i.e., the differential attenuation in the location of the step loss did not change. (c) When the step loss is different in the Stokes (0.2 dB/m) and anti-Stokes (0.25 dB/m) signal, i.e., the differential attenuation in the location of the step loss did change.

Also, we realize that we were unclear in the manuscript and we have modified it to be more clear:

“Here, we present a new method to calibrate temperatures along the fibers for single-ended measurements. We recognize that it is also necessary to present a calibration method for double-ended measurements, especially for damaged or strained cables that have spatially variable differential attenuation. However, because the differential attenuation along the length of our cable was fairly constant 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 will continue to be addressed in future investigations.”

P36 L16: Write the equation as a numbered equation to make the methods more clear: this equation is needed in Eq 2-4 again.

Thanks, we have written this equation as a numbered equation to be more clear.

P36 L21-24: The native calibration also uses Eq 1-3, right? Explain how gamma is determined, and which points of known temperature they use. Are alpha and C determined for each time step or a priori (I think both are possible).

Please note that:

1) As described in the manuscript, the manufacturer-internal calibration (native calibration) also uses Eq. 1-3 and assumes that gamma is known ahead of time (i.e., it has a default value on each DTS instrument that cannot be changed).

2) The steps needed to calibrate the temperature along the fiber using the manufacturer-internal calibration are fairly well documented in the manual of the instruments (as explained before).

3) Because calibration methods of DTS software are proprietary information, we cannot provide a detailed explanation of the manufacturer-internal calibration method.

4) For both calibration methods (manufacturer-internal and extended), alpha and C can be estimated for each time-step (typically referred to as dynamic calibration) or can have a fixed value (typically referred to as fixed calibration). In the manuscript, we used dynamic calibration for both methods (to be consistent) and we were clear saying that the calibration parameters are recalculated for each time-step (pp37, L12-14).

That being said, we think that this comment should not be specifically addressed in the manuscript.

P37 L15-25: This should be in the section ‘experimental setup’.

Please see response to comment P34 L21 (above). Thanks.

P38 L16: I would leave this section out, or much more detail about the calibration of a double ended measurement should be given. But since the main focus is on single ended measurements, I would leave this out.

As explained above, the objectives of this study are not only limited to the manual calibration method. This section does not deal with calibration at all. Instead, it tries to inform the reader that the decision of using single- or double-ended measurements depends on each installation. Therefore this needs to be checked. For this reason we believe that details about the double-ended calibration are not needed, and that the explanation of double-ended measurements is sufficient. In the same way, this section also explains that the integration time affects the temperature measurements and tells the reader that the integration time needs to be defined to be able to see the physics behind the environment that is being measured.

We have added the following paragraph in the manuscript (at the beginning of this section) to be clearer:

"Selection of single- or double-ended measurements needs to be analyzed because it can result in different degrees of accuracy and temperature resolution. While single-ended measurements provide more precision near the instrument, double-ended measurements allow the users to accurately derive temperatures from fibers with spatial variation in the differential attenuation of the backscattered signals, which typically occurs in damaged or strained fibers."

P41 L12-13: It is clear that you use the average temperature over 10-25m, but which values of z1, z2 and z3 are used in Eq. 2-4? Also add a sensitivity analyses for different z values. For example: How are the temperatures influenced if z1=10m compared to z1=25; what if T(z1) is between 10 and 15m and T(z2) is between 20 and 25m; What if z3 = 30-45m etc.

Thanks, we appreciate this Referee's comment because we believe that it can greatly improve the quality of the manuscript.

In the manuscript we used sections (instead of points) of known temperature to determine the differential attenuation. Using equation 2, we estimated the differential attenuation for each point (i.e., for each position reported by the DTS instrument) within the section, and then we used the mean value of the differential attenuation in this section as the differential attenuation of the entire cable (remember that we assumed that the differential attenuation is not spatially dependent). After knowing the differential attenuation, equation 3 is used to estimate "C". Here, you can select any points (z1, z3) within the sections of known temperature to determine the value of R(z1) and R(z3). After knowing "C", equation 4 is used to estimate "gamma". Here, again you can select any point within the section of known temperature, but note that the quality of the calibration may depend on the points selected (although it is more important the length of the calibration section than the selection of z1 or z3 – as described below).

We have clarified the methods section of the manuscript to clarify the method when sections are used:

"When sections (instead of points) of known temperature are used to estimate the calibration parameters, the differential attenuation is calculated using the mean value of the $\Delta\alpha$ of contiguous points within the section, then C and γ are estimated using equations (4) and (5)."

We have also clarified our method in the results and discussion section:

“To illustrate the extended 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 manufacturer-internal-calibrated temperatures. The mean value of the $\Delta\alpha$ was calculated from two sections on the optical fiber held at the same temperature (between 10 and 25 m and between 370 and 385 m, in the cold bath at ~19.6 °C, as shown in Figure 2). The values of *C* and γ were calculated from two points on the fiber held at different temperatures (z_1 = 17.5 m at ~19.6 °C in the cold bath and z_3 = 347.5 m at ~61.5 °C in the hot bath).”

As suggested by the referee, we performed a short sensitivity analysis. We used the root mean square error (RMSE) and the standard deviation of the points of known temperature along the cable to determine the goodness of the agreement between these calibrations.

We have included this analysis in section 3.1.1:

“The length of the known-temperature section and the selection of z1 and z3 may have an impact on the quality of the calibration. A sensitivity analysis showed that the effect of the selection of z1 and z3 on quality of the calibration is negligible compared to the effect of the length of the known-temperature section (data not shown). Table 1 show that both the RMSE and the standard deviation of the extended-calibrated temperatures in the calibration baths are reduced as the length of the calibration section is increased. Thus, longer calibration sections are recommended for improved temperature resolution.”

Table 1. Sensitivity analysis of the extended calibration for different lengths of the calibration sections.

Length of known-temperature section	RMSE (°C)	standard deviation (°C)
1 m	2.077	0.051
5 m	1.532	0.044
10 m	0.556	0.038

P42 L23: As said before: I would leave this part out.

Please see response to comment of P38 L16 (above). Thanks.

P44 L2-11: Shorten this part, because in principle this can be done with classical sensors as well. Just emphasize the main advantages of DTS above classical sensors (as is shown in Fig 5).

Thanks for this comment. We have shortened this part.

P44 L13-26: Leave this part out. It is outside the scope of the paper.

We have shortened this part and only leaved general information of the results obtained with the DTS system. Please also note that these results are hard to achieve using traditional sensors and thus, show advantages of the vertical high-resolution DTS system.

P45 L22-29: Outside the scope of the paper.

We have shortened this section. Now we only have information needed to compare the DTS system with more traditional sensors and the reader has been referred to another work for more details about these experiments.

P46 L19-21: Leave out the sentence: 'This erosion … 2010a).'

Corrected

P47 L21-22: leave out 'and zenith … 2010).'

Corrected

P48 Summary and conclusions: Emphasize the advantages of DTS above classical T sensors and tell the difference in performance between native and manual calibrated temperatures.

We have revised the summary and conclusions:

"Summary and conclusions

As temperature is a major driver of changes in natural and managed aquatic 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 in many hydrological applications such as thermohaline environments. In addition, the presented 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 extended-calibrated temperatures resulted in a more robust and usable data set than the manufacturer-internal calibrated-temperatures. The presented 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. In our experimental setup, 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."

Figure 1a: The picture of the constructed DTS pole does not add any information. Either put in another picture (maybe with a detail of splice 2) or leave it out. Figure 3c: zoom in to better show the differences between manual and native calibration. This is important, because the current figure doesn't convince me to put more effort in manually calibrating the signal.

Fig 1a: We respectfully disagree with the referee. Even though the picture of the constructed DTS pole does not add any technical information, we believe it is important for a paper that discusses novel instrumentation to show the reader what that instrumentation looks like as it is used.

Fig 3c: Please note that this is the first attempt to try to clarify how to recalibrate DTS data and to "reveal" a little the DTS theory, which has been "obscure" in the hydrologic community. In this investigation, we did not have significant changes in the optical properties of the fiber, and for this reason the results of the extended (or manual) calibration are relatively similar with the manufacturer-internal (native) calibration (with extended-calibrated temperatures having a small RMSE than manufacturer-internal calibrated temperatures). However, there are other situations in which the differences between these two calibration methods are important. In these situations, DTS users are forced to put more effort to post-process the data (because using the manufacturer-internal calibration method result in large disagreement of the temperatures in sections or points of known temperature). This is the first investigation that gives insights about this issue and provides users a basis to check the manufacturer-internal calibration.

Figure 4b: leave out, this is outside the scope of the paper.

We respectfully disagree with the Referee. This figure show important features that are hardly achievable using traditional moderate-cost temperature sensors (e.g., see inset (zoom-in) putting attention in temperature and spatial resolution). Also, this figure helps the reader to understand better Figure 4a.

Technical corrections:

P31 line 2: what kind of other practical limitations?

We have modified the manuscript to include an example of practical limitations:

"Measuring temperature at these scales, especially when diurnal cycles need to be recorded over a long time period, can be difficult because of the cost involved (Branco et al., 2005) and other practical limitations, such as placing multiple sensors in a limited space. Multiple sensors need to be independently calibrated and may be subject to different intensities of drift in thermohaline environments (Bergman, 1985)."

P31 L24: 0.01 degree C can be achieved when averaging over 30 min

Thanks, this has been modified in the final version of the manuscript

P34 L2: skip 'main', unless there are more objectives.

As explained before, we have revised our objectives (see responses above)

P36 L3: change 'the presentation of' into 'to present'

Corrected

P36 L12, 13 and 17: add units for DeltaE, k and Is

Corrected

P36 L26: I wouldn't call it 'manually calibration', but something like improved or extended calibration.

We have revised the names of the calibration methods. The "native calibration" now is called "manufacturer-internal calibration" and the "manually calibration" now is called "extended calibration". Thanks for this comment.

P38 L11: a single trace is 1 measurement, right?

A single trace corresponds to the temperature measurements along the entire fiber optic cable for a duration of one integration time. We have modified the introduction of the manuscript to clarify this term:

"DTS technology uses Raman spectra scattering in a fiber-optic cable to measure temperatures along the cable length (this is referred to as the temperature trace)."

P40 L9: Is Fig. 2b obtained with the native or manual calibration method?

Figure 2b was obtained with the manufacturer-internal calibration method. We have modified the figure caption to be clearer about this:

Figure 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 measured during the experiment (obtained using the manufacturer-internal calibration method). The black line was obtained at the beginning of the experiment and the orange line was obtained after 15 days.

P42 L25: Are both single and double ended measurements calibrated with the native method?

Yes. For clarity, we have modified the caption of Table 2 in the following way:

Table 2. Comparison between single-ended (SE) and double-ended (DE) measurements in the hot bath (obtained using the manufacturer-internal calibration method). T is average temperature and σ is standard deviation.

P46 L22: give 'the radiative heating experiment' a different name, or change it into 'The effect of radiative heating is shown in Fig 6.'

Thanks, this has been changed in the revised manuscript.

P48 L6-7: Change 'not only in understanding the physics of solar ponds or other thermohaline environments but of the majority of shallow water bodies' into 'in many hydrological applications'.

Thanks, we have changed this in the revised manuscript.

P48 7-8: leave out

Corrected

P48 L14: 'present' should be 'presented'

Corrected

P48 L22: Add: 'In our experimental setup, radiation absorption was found…'

Corrected

Table 1: Are these results of the native calibration?

These are results of the manufacturer-internal calibration. We have clarified this in the table caption.

Figure 1b: indicate the locations of z1, z2 and z3

We believe that adding these locations in this figure will result in a very busy figure. Instead, these locations have been highlighted in Fig. 2b.

Figure 2: indicate the locations of z1, z2 and z3 and indicate which calibration procedure was used to obtain Fig 2b.

Thanks for this comment. We have highlighted the locations of z1, z2, and z3 in this figure. Also, we have been more clear throughout the manuscript regarding the calibration procedure used.

Figure 5: Also indicate here which calibration procedure was used.

Please note that we only used the extended (manual) calibration method only in the corresponding section. Recall that presenting this manual method is only one of the objectives of our paper, and not the only one. We want to apologize to the Referee because we realize that we need to be clearer to avoid this confusion, which is one of the main concerns that the Referee had.

Figure 6: Also indicate here which calibration procedure was used. Looking at the noise below 50 cm (Fig 6b), I guess it is the native calibration, since the noise seems larger than 0.035 C.

These results were obtained using the manufacturer-internal calibration method. The noise in the lower convective zone occurred because these measurements were performed using a 10-seconds integration-time interval to be able to capture potential fast changes in the thermohaline environment when the DTS pole was shaded (as opposed to the 5-min integration time used elsewhere in the manuscript). We apologize because we did not include this important information in the methods section. We have modified the caption of Figure 6 to include this information:

Figure 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. <u>These measurements were obtained using a 10-seconds integration-time interval and using the manufacturer-internal calibration method</u>.

In the methods section, we have also specified the integration time of the measurements:

"…Then, the pond was typically exposed to the artificial lights 12 hours per day (from 6:00 a.m. to 6:00 p.m. with the exception of the first day that was from 9:00 a.m. to 6:00 p.m.) and <u>its thermal response was monitored using 5 min integration-time intervals</u>.

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 (Figure 1a). Holes were made in the shield to allow air (above the water surface) and water to move across it. The DTS pole was covered for approximately 60 min until a new steady state was reached. After this, the DTS pole was uncovered and <u>temperatures were recorded using 10 s integration-time intervals</u> until the initial value was reached."