Authors' response to referee 1

General comments:

It is not a difficult task to go through this manuscript. On the one hand it is well organized and structured, which makes me quickly grasp all the important points the authors want to illustrate. However, on the other hand I have to say that all the results in this research (e.g. air temperature in the region strongly increased in the last several decades which elevated water temperature and Schimdt Stability) is not so new to me, and it gives me a feeling that if its research place changed to somewhere else then the results will be quite similar to those in some previous studies. The authors said the innovation point is that most of previous research neglected the climate change effects on small lakes, which is not true for me. In recent years there are already some research on this topic (see my comments below). For my point of view the innovation points in this paper is the application of 3D model to check influence of climate warming on lakes based on long-term simulations, and this should be reflected in the Results and Discussion (see my comments below).
To avoid the misunderstanding, I do not say this research is bad, instead I recommend the authors inputting some new findings, as suggested below, to make the manuscript more attractive.

> **Authors' response:** First of all, my co-authors and I would like to thank you for the interest in our work and for this review.
> We agree on the general consideration that, if the study site under consideration changed, the results would be close to those found in previous studies. On the first hand though, this remark adds some robustness to our modelling set up as well as to our findings. On the second hand, the main idea behind this work was not only to evaluate the 3D effects of climate change on a single small polymictic lake, but also to propose an approach able to generalize to some extent the results to the numerous similar ecosystems that fit into the similar temperate climatic conditions and morphologic characteristics. In our revised manuscript, we focus more closely on this aspect.
> We agree on the general remark that a stronger focus on 3D results is needed in order to highlight the novelty of the approach. This is addressed in the revised draft both in the results and in the discussion section.
> Concerning the novelty of our results, we do not see the innovation in this paper lying only in the application of a 3D model. Even though this is surely one of the main innovative points of the work, also the use of the SAFRAN reanalysis to hindcast the lake hydrodynamics and the use of high-frequency data for including daily cycles in the calibration and validation of the model constitute innovative elements, especially for small urban lakes. Finally, also the use of ecology-derived indices (such as the growing degree days) as proxies for the impact of climate on potential biomass growth in aquatic ecosystems adds an element of innovation.
> Finally, it is true that our writing did not highlight enough these additional elements of novelty, that should now be more clearly brought to the attention of the reader in the revised version.

Detailed comments:

Line 29: This sentence is not so reasonable, since recently there are quite a few studies to check the response of small lakes to climate change, like:
1. A small temperate lake in the 21st century: Dynamics of water temperature, ice phenology, dissolved oxygen and chlorophyll a
2. Future projections of temperature and mixing regime of European temperate lakes.
It is better to further modify this sentence, to make it a bit soft.

> **Authors' response:** Thank you for these references, now cited in the revised version. However, the intention behind the sentence under examination was to highlight how small polymictic lakes have received

overall less attention than, for instance, larger mono- or dimictic lakes. The paragraph was modified (see italics) into:

"On the other hand, small and *shallow lakes (i.e. with surface < 1 km^2, and light potentially penetrating to the bottom (Meerhoff and Jeppesen, 2009)) have received less attention in climate change impact studies than deeper monomictic or dimictic water bodies*. Nevertheless, they play an important role for biodiversity and are prone to ecological deterioration and harmful algal blooms (Biggs et al., 2016; Wilkinson et al., 2020). Furthermore, with the advance of urbanization, the presence of aquatic environments has become a key feature for the improvement of life quality in the urban landscape (Frumkin et al., 2017; van den Bosch and Sang, 2017). Often small and shallow, urban lakes grant valuable ecosystem services and contribute to the preservation of biodiversity (Frumkin et al., 2017; Hill et al., 2017; Hassall, 2014; Higgins et al., 2019). *For these reasons, in recent years small polymictic lakes gained greater attention in scientific studies.* However, to our best knowledge, only a few studies have quantified the effect of climate change on these ecosystems (*Tan et al., 2018; Shatwell et al., 2019*, Moras et al., 2019)."

Line 57: Better to slightly modify it like, "Although the proposed ....., it is generic and...."

Authors' response: The sentence has been modified into: "*Although the proposed methodology was here applied to a study site located in the Paris region, it is generic and could be applied to other similar sites*."

Line 101: I am not so sure whether it is reasonable to use "constant values for sky cloudiness". Since in this way incoming longwave radiation only depends on air temperature which may make the results not so accurate. What do you think of it??

Authors' response: We agree that it would be preferable to use cloudiness measurements. Cloud cover measurements were available from the closest meteorological station, 24 km away, but not for the 8x8 km SAFRAN reanalysis cell, contrary to other meteorological variables.
The model was tested during calibration and validation using two different modules for heat exchange, the Ocean model with time series of cloud cover, and the Murakami model which is implemented with a constant cloud cover in Delft3D. Overall, water temperature was slightly better modeled by the Murakami model with a specifically calibrated value for cloud cover. For instance, for the year 2016, RMSE at site A was around 1.1°C for all three depths with the Ocean heat exchange model, while it was around 0.8°C for the Murakami heat exchange model.
This can be explained on the first hand by the high uncertainty that affects ground-based cloud cover observations (Silva and Souza-Echer, 2015, Zelinka et al., 2017) and by some gaps found in the series, and on the second hand by the different source of these data from the other meteorological input. Furthermore, a preliminary analysis that we carried out on 19 years (from 2000 to 2018) of cloud cover data from the closest meteorological station, showed an overall very low seasonality in the series, (with 7 oktas (87%) being the most probable value for all seasons and 65% being the overall mean value) and no interannual trend. The absence of strong climatic trends for the area of interest in terms of cloud cover is confirmed by Pfeifroth et al. (2018).
We therefore decided to use the constant calibrated value of sky cloudiness in order to achieve the best results in terms of simulated water temperature against our set of hourly averaged water temperature observations. In any case, this led to very good model performances during both calibration and validation.
Finally, we think that the calibration of the parameter to a value of 80% does not introduce considerable biases in our work, even in the long term study, also given the non-negligible uncertainty that affects cloud cover observations.

Line 108: for the part 2.2.2 Meteorological input data, If you used the historical reanalysis climate data to drive the hydrodynamic model, I supposed it is better to firstly show the accuracy of this reanalysis in capturing the real climate condition. Have you compared the reanalysis results with the real measurements??

Authors' response: A thorough validation of SAFRAN can be found in Quintana-Seguì et al. (2008), where SAFRAN is compared directly with meteorological observations. Air temperature, wind speed, relative humidity and incoming solar radiation are well reproduced by SAFRAN with small bias and high correlation with observation series. For our study site, we obtained very similar correlation and RMSE values during a preliminary comparison between SAFRAN data and time series from the closest meteorological station. In the revised draft, we explicitly mention the process of validation of the SAFRAN data around lines 116 and 123 (see italics):

"SAFRAN integrates spatialized data from meteorological models with various sources of observations through data assimilation techniques, in order to create a consistent and spatially detailed record of meteorological data over the French territory. *The accuracy of the SAFRAN reanalysis has been thoroughly validated by comparison with observed data series (Quintana et al., 2008), and the reanalysis data were tested as inputs to hydrological models (Raimonet et al., 2017) with success*. Reanalysis data were downloaded from the SAFRAN suite in terms of: air temperature [°C], specific humidity [-], solar radiation (direct and diffused) [$W.m^{-1}$] and wind speed [$m.s^{-1}$]. *All these variables are very well reproduced by SAFRAN (Quintana et al., 2008).*"

For Figure 2: the legend doesn't match with the plot, please modify it.

Authors' response: The figure under examination will change in the revised draft to allow for a deeper discussion of the calibration and validation of the model (see Figure 1 in this document). Parity diagrams between observations and simulations were added for three layers (panels a, b and c), and the timing and frequency of modeled and observed stable stratification events were also addressed. The caption and legend have changed accordingly:

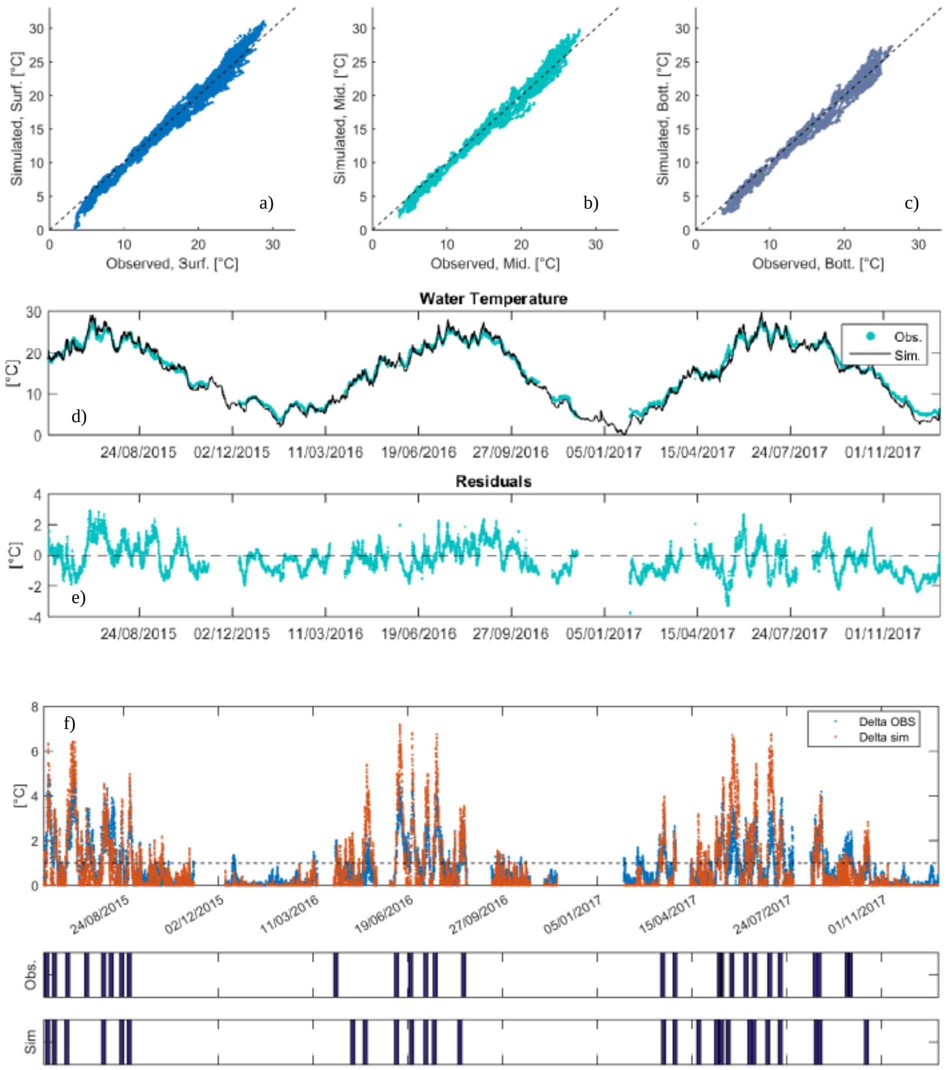

Figure 1: Model performance during validation at site A. Panels a, b and c: parity diagrams between simulations and observations for the surface, middle and bottom layers, respectively. Panels d and e: visual comparison of simulated and observed water temperature at the middle layer (d) and corresponding residuals (e). Panel f: modeled (orange) vs. observed (blue) temperature difference between surface and bottom layer and comparison between the timing of observed and modeled stable stratification events.

Line 299: For Schimidt stability it is not quite meaningful to show the result in winter, instead it is better to analyze it in summer which should be input into Figure 4c.

Authors' response: Schmidt stability was analyzed during Summer but did not show any significant trend, and for this reason it was not shown in figure 4, as stated in the caption. However, it was probably unclearly explained, and it is true that we did not further comment this point in the discussion. The absence of a trend in the summer average of Schmidt stability is a relevant result, as it marks a strong difference from dimictic or monomictic lakes. We therefore extended our discussion on this matter:

"D*espite a strong augmentation in water temperature, stratification did not show any significant increase during Summer. This is due to the shallowness and polymicticity of the study site, that allow the bottom layer to be heated and the water column to be mixed frequently even during Summer. Summer surface and bottom water temperatures increased at a very similar rate over time (0.7°C.dec^{-1}), preventing significant changes in the Schmidt index and in the number of SSD. This result marks a strong difference with the reported behavior of deeper monomictic or dimictic lakes, where the stable seasonal stratification can induce an intensified warming of the surface mixed layer, enhancing in turn the Schmidt stability (e.g., Livingstone, 2003, Vinçon-Leite et al., 2014). Analyzing long term simulations of three lakes of different* *average depths, Magee et al. (2017) found significant increases in summer Schmidt stability only for the two deeper study sites."*

For part 3.3 Spatial analysis of stratification: I mean this part is not new to me. It is very normal that the shallow part of a lake experiences less stratification compared to the deep part. I recommend that the authors also check the horizontal distribution of other thermal indices, like mixed layer depth, thermocline depth, which may provide some interesting findings.

> **Authors' response:** Thank you for these suggestions to deepen the analysis of the 3D capability of the model. We analyzed the spatial distribution of the thermocline depth. However, the definition and analysis of thermocline (or mixed layer) depth on a polymictic water body with stratification events from 1 to 10 consecutive days is quite challenging. On the long-term, no significant trend was detected, neither were horizontal patterns in its spatial distribution.
>
> To complete the study, we also extended the spatial analysis to the two ecology-derived indices (growing degree days (GDD) and number of growing days (NGD)), with the objective to detect the presence of some spatial niche favorable to phytoplankton species with high optimum temperatures (such as cyanobacteria).
>
> Three values were tested for the base temperature in the calculation of GDD and NGD (4°C, 18°C and 25°C). These values were selected since they respectively constitute baseline temperatures for (i) overall biomass growth and species able to grow at low temperature such as diatoms (after Dupuis and Hann, 2009), (ii) most phytoplankton species, normally growing at medium / high temperatures (such as dinoflagellates or green algae), and (iii) intense growth of cyanobacteria (Paerl, 2014). Results of this analysis are reported here only for GDD in Figure 2. The top three panels show the overall time-average of the annual values for GDD, calculated with the three different base temperatures (4°C, 18°C and 25°C from left to right), while bottom panels show the mean intensity of the monotonic trend for each cell in the domain, when statistically significant.
>
> Results using T_{base}=4°C and T_{base}=18°C show weak horizontal gradients (around 1% and 3%, respectively) in the distribution of GDD and no easily interpretable patterns in the intensity of their growing trend. When using T_{base}=25°C, horizontal gradients grow considerably, both for the overall time-average of GDD (around 4%) and for its growing trend (around 8%).
>
> While optimal thermal conditions for cold- and medium-temperature species are quite uniform in space, and have evolved quite uniformly over time, it is not the case for species with high optimum temperatures.
>
> This suggests the existence of a region, the shallower north-eastern part of the lake, particularly favorable to the development and dominance of toxic species such as cyanobacteria. Furthermore, this spatial heterogeneity is increasing over time (see fig. 2-f). This region of the lake could also become more favorable to the initiation of cyanobacteria blooms.
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> Finally, this shows how observations taken at one single site as well as 1D models might only be partially representative of overall dynamics of a water body, especially for shallow water bodies with strong relative bathymetric variations.

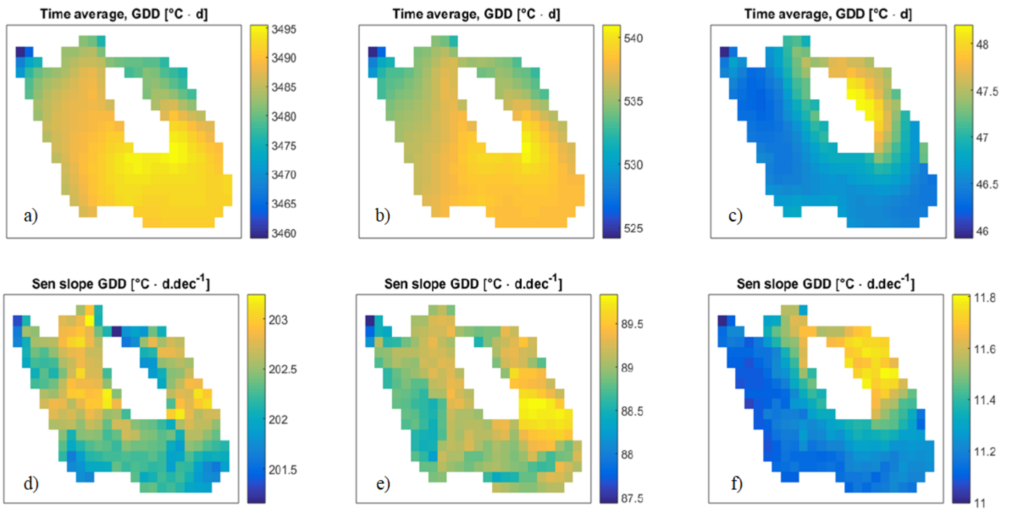

Figure 2: Spatial analysis of GDD. Different base temperatures were tested for the calculation of the GDD and the relative trends; they are represented along the three columns: first column: T_{base}=4°C, second column T_{base}=18°C, third column T_{base}=25°C. Panels a, b and c represent, for each cell in the domain, the average over the 58 years of simulation of annual values of GDD. Panels d, e and f show, for each cell in the domain, the average interannual trend calculated through the Sen slope (all Mann-Kendall tests were statistically significant).

For 4 Discussion: Just as I suggested before, results in this paper is not so new compared to those from previous studies, as well as the Discussion. The innovative points, based on my opinion, is the application of 3D model to check the influence of climate change on lakes. Consequently there should be more discussion, at the last paragraph of this part, on how the heterogeneity of thermal structure in the horizontal direction can affect the aquatic ecosystems,

Authors' response: The exploitation of 3-dimensional results are expanded in the revised draft, with the spatial patterns evoked in figure 2 for GDD. In the revised draft, the appropriate paragraphs in the Materials and methods, Results and Discussion sections are modified according to the results briefly discussed here for figure 2. We further develop our discussion section highlighting the new insights coming from 3D modelling on the spatial heterogeneity of the thermal dynamics in a shallow polymictic lake, based also on the spatial analysis of GDD presented in our previous response.

Bibliographical references

"Warm spring and summer water temperatures in small eutrophic lakes of the Canadian prairies: potential implications for phytoplankton and zooplankton". Dupuis and Hann, 2009.

"Mitigating Harmful Cyanobacterial Blooms in a Human- and Climatically-Impacted World", Paerl H. W., 2014.

"Trends and Variability of Surface Solar Radiation in Europe Based On Surface- and Satellite-Based Data Records", Pfeifroth et al., 2018.

"Analysis of Near-Surface Atmospheric Variables: Validation of the SAFRAN Analysis over France", Quintana-Seguì et al., 2008.

"Ground-based observations of clouds through both an automatic imager and human observation", Abel-Antonio Silva and Souza-Echer Mariza Pereira, 2016.

"Clearing clouds of uncertainty", Zielinka et al., 2017.