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Hydrology and Earth System Sciences
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Discussions

Interactive comment on "Future projections of temperature and mixing regime of European temperate lakes" *by* Tom Shatwell et al.

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We thank referee #1 for her/his time and effort in formulating helpful comments.

Comment: The title does not completely reflect the content of the manuscript.

Answer: We respectfully disagree. The title reflects exactly what the reader will find in the paper. All the lakes considered in the study are European temperate lakes, located in the area not affected by marginal influence of neighbouring climate zones, whether Mediterranean, alpine, or boreal. Moreover, the four lakes are all representatives of the major lake seasonal mixing types found in temperate climates providing the modeling results with generality. Citing Reviewer2, who explicitly underlined the background idea of our study setup, "...all lakes used in this study have different combination of morphol-

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ogy and mixing regime, yet they are situated rather close to each other, what makes analysis even more interesting and relevant...Paper title clearly reflects the contents of the manuscript...".

Comment: Global climate scenarios are used as is without considering bias correction of any kind. How does RCA4 temperature bias affect the conclusion of the current study?

Answer: See our reply to the specific comment on bias below.

Comment: Precipitation is not mentioned as input to FLake model. However, in winter snow can reinforce substantially lake insulation in presence of ice. In RCA4 precipitation is also biased. Is the snow module activated in FLake? Please add a comment on that particular point and discuss how snow could modulate the conclusions of the paper, at least in the close future before the warming prevents ice formation

Answer: Precipitation did not enter the model directly, neither was the snow included into the ice modeling. There are several indications suggesting that including the snow as model input would not improve the predictive value of the model outcomes: (i) The current version of FLake treats the thermal regime under ice in a simplified way, without taking into account the short-wave radiation penetrating into the water column under the ice cover. In that sense, adding the snow as an insulation for the radiation flux does not change the mixing physics of the ice-covered period much. (ii) In temperate regions, the relatively short ice-covered periods on lakes are weakly affected by the snow cover compared to e.g. boreal and arctic lakes. This fact was also supported by the study of the FLake performance for the ice modeling on Lake Müggelsee (Bernhardt et a. 2012). Taking also into account the additional uncertainty related to the absense of exact information on snow proportion, the complex snow and ice rheology at temperatures close to the melting point, and the general shortening of the ice cover period in the future scenarios, an inclusion of precipitation into scenarios did not seem reasonable. /a version of this passage can be included into the paper for clarity/

Comment: Flake is calibrated with ERA-Interim data, it is not clear however which calibration period was used: figure 3 indicates 1996-2002 but this is not explicitly stated in the paper.

Answer: We assessed model performance using temperature profiles in the period from 1979 to 2014 in Müggelsee (measured weekly, and from 2004 to 2014 hourly to assess short-term stratification), from 1979 – 2001 in Heiligensee (monthly), from 1991 to 2012 in Stechlinsee (weekly to monthly), and from 1979 to 2010 in Arendsee (weekly to monthly). This sentence can be added to the revised manuscript.

Comment: Calibration of FLake parameters allow correcting biases in ERA-Interim forcing (Biases due to daily variables, to sub-daily interpolation, etc.). For the future period 2020-2100, it is not proven that these calibrations are best when forcing is made with RCA4. I encourage authors to compare RCA4 model runs for present period with and without calibration, using ERA-Interim as lateral boundary conditions, and discuss the impact in terms of surface temperature, icing, wind-mixing regimes, etc.

Answer: This is of course true, however, we not only used the RCA4 model in the ensemble, but a total of different 5 regional climate models (CCLM4-8-17, REMO2009, HIRHAM5, RACMO22E, RCA4), each with their own bias. In fact, each of the 12 GCM-RCM combinations has its own bias, which would imply 12 different calibrations to account for both RCM and GCM bias. We chose to use ERA-Interim here so that we could work with only one parameter set. Nevertheless, the potential bias is a good point, so we reran the model (with the parameterization used for the manuscript) with the historical hindcast of each of the 12 GCM-RCM combinations in the ensemble, and calculated the bias of the key variables (temperature, mixing etc - see below) we analyzed, as the reviewer suggested. The mean bias of each variable forced by the ensemble hindcast barely differs from the bias obtained using ERA-Interim. With the parameterization we used, the ensemble showed on average a smaller absolute bias in bottom temperature, mixed layer depth, stratification duration and stratification onset timing and a slightly greater bias only in surface temperature and stratification breakdown timing. This provides high confidence that our results and conclusions are relatively unaffected by bias. We will include this information and discussion of the consequences in a revised manuscript.

Bias for key lake variables with the model (forced by ERA-Interim / the ensemble, same model parameters).

Ts (degrees C): Müggelsee: -0.67 / -0.83, Heiligensee: -1.07 / -0.82, Stechlinsee: -1.83 / -2.21, Arendsee: -1.06 / -1.39

Tb (degrees C): Müggelsee: -1.72 / -2.14, Heiligensee: -1.22 / 0.08, Stechlinsee: -0.29 / 0.06, Arendsee: 0.22 / 0.31

hmix (m): Heiligensee: -1.56 / -1.12, Stechlinsee: 1.20 / -0.13, Arendsee: -2.1 / -0.85

Stratification duration (d): Heiligensee: -35.3 / -20.9, Stechlinsee: -39.4 / -37.1, Arendsee: -21.2 / -18.1

Stratification begin (day of year): Heiligensee: 8.6 / 13.5, Stechlinsee: 16.9 / 9.3, Arendsee: 5.8 / -0.1

Stratification end (day of year): Heiligensee: -1.9 / -20.6, Stechlinsee: -18.5 / -28.3, Arendsee: -15.3 / -18.4

Comment: In Müggelsee a specific calibration is performed to account for a water supply from a connected river. Is there any signal in climate simulations that confirms this river discharge will be as important as in the present climate? A smaller discharge in the future (due to less precipitation, more evaporation, etc.) would for instance impact transparency and change the calibration results.

Answer: Our scenarios assume a conservative behavior with respect to the river discharge. While effects of the changed river flow on the temperature and mixing regime can indeed be manifold, their assessment requires more detailed information than a simple scenario for an average discharge. The atmospheric influence remains however a primary factor for the physical processes in lakes, hence the focus of model scenarios on the lake-atmosphere interaction. Moreover, as the reviewer suggested, another important factor is transparency. However, it is unclear how this will change, with reports in the literature that it is likely to both increase and decrease. It is linked to runoff, carbon export and nutrient loading. For this reason we performed the sensitivity analysis with transparency, and found that changes in transparency near the current values are unlikely to substantially alter the thermal response of the lakes to warming.

Comment: In figure 9 only the 2050-2059 period is considered? Are the results also valid for the other time periods? Please add a comment on that point page 10.

Answer: Yes the results are valid for those periods too in the sense that the pattern and relationship to extinction is the same (compare Fig 1 and Fig 2). The absolute values of stratification duration of course change somewhat with warming. We added a comment in this regard to the revised manuscript.

Comment: The ensemble of 12 members is not discussed in terms of dispersion: a rank diagram of air temperature is probably very important to discuss the ensemble model dispersion and demonstrate this ensemble is enough-dispersive to represent the climate variability.

Answer: We created rank (cumulative distribution) diagrams of the monthly and annual mean temperatures of the historical scenarios of the ensemble and compared these with the corresponding temperatures of the ERA-Interim reanalysis and the actual measured air temperatures at the Menz weather station for the period 1991 to 2010 (Fig. 3). The figure shows that the dispersion of the ensemble is quite comparable to that of both the ERA-Interim and the observed data. The ensemble tended to slightly underestimate the frequency of extremely warm months in the upper 10th percentile (a) but not the frequency of warm years (b). This may affect our estimates of peak summer temperatures in all lakes and the frequency of extended stratification events during heatwaves in polymictic Müggelsee. However, it should not influence our overall conclusions. This will be included in a revision.

Comment: Sine data are used to reconstruct wind which is a key variable for the mixing-regime of lakes. It is not clearly proven how accurate wind reconstruction is and how it compares to Potsdam dataset. Please indicate Potsdam location in Figure 1.

Answer: The algorithm for generating the subdaily data accurately reproduced the complexity of the observed windspeed dynamics, as shown in Fig. 4. It produced realistic behavior of day-to-day windspeed (Fig 4a), as well as the hourly variation of mean windspeed and associated variability (Fig 4b, c), and also the seasonal change of this hourly variation (Fig 4b, c), while still preserving the given daily mean windspeeds (Fig 4d). We mistakenly stated that the algorithm was based on Potsdam weather data. In fact it was based on the weather data from the Menz station, located 5 km from the shore of Stechlinsee, about 100 km north of Potsdam. The map in Manuscript-Fig 1 is unable to resolve this small distance, so we added it in the text.

Comment: Temporal downscaling of humidity is performed linearly. Is it relative humidity that is considered as input to FLake? Usually specific humidity is used. Please clarify.

Answer: Yes Flake uses specific humidity as input. We tested this interpolation approach against the observed weather data at the Menz station. Assuming linear day-to-day variation of specific humidity, we calculated the diurnal variation of relative humidity based on the diurnal variation of air temperature used in our approach. This disaggregated relative humidity matched the diurnal variation of observed relative humidity very closely.

Comment: In the presentation of FLake model runs, it would have been helpful to clearly explain which time step was used: sub-daily variables are constructed but then is the atmospheric forcing 6-hourly, 3-hourly, etc.?

Answer: True, we used 6-hourly atmospheric forcing, constructed from the daily values.

The sentence now reads: “These variables were available at daily resolution in the climate projections, and were downscaled for model simulations to 6-hourly resolution with the same daily mean to account for diurnal forcing.”

Comment: Page 9 line 9: ensemble; Page 12 line 25: transparency; Page 12 line 28: Heiligensee

Answer: Ensemble is corrected, thanks, but transparency and Heiligensee seem okay?

Reference: Bernhardt, J., et al. (2012). "Lake ice phenology in Berlin-Brandenburg from 1947-2007: observations and model hindcasts." Climatic Change 112(3-4): 791-817.

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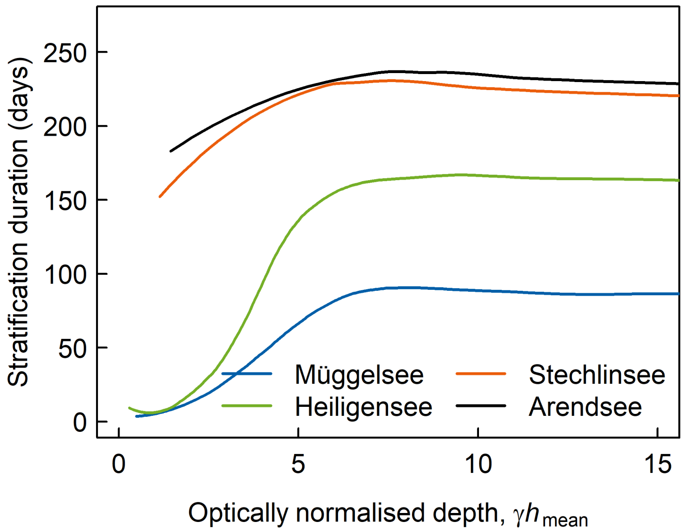

Fig. 1. Effect of averaging period on Manuscript-Fig 7: the relation for the averaging period 2010-2019.

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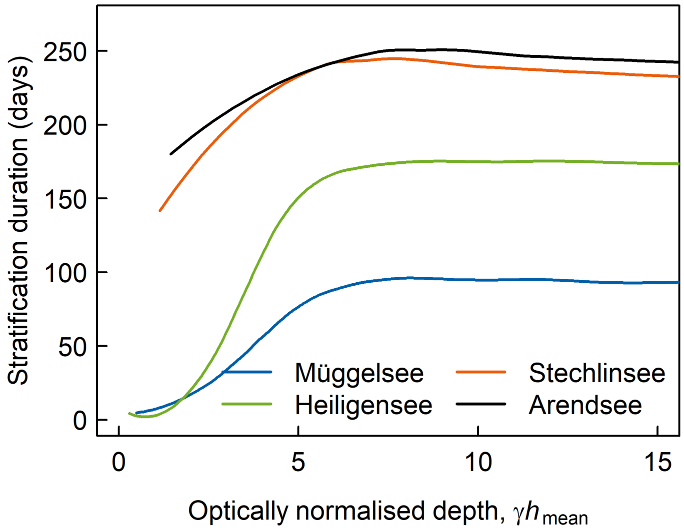

Fig. 2. As for Fig 1 but calculated with averaging period 2090-2099.

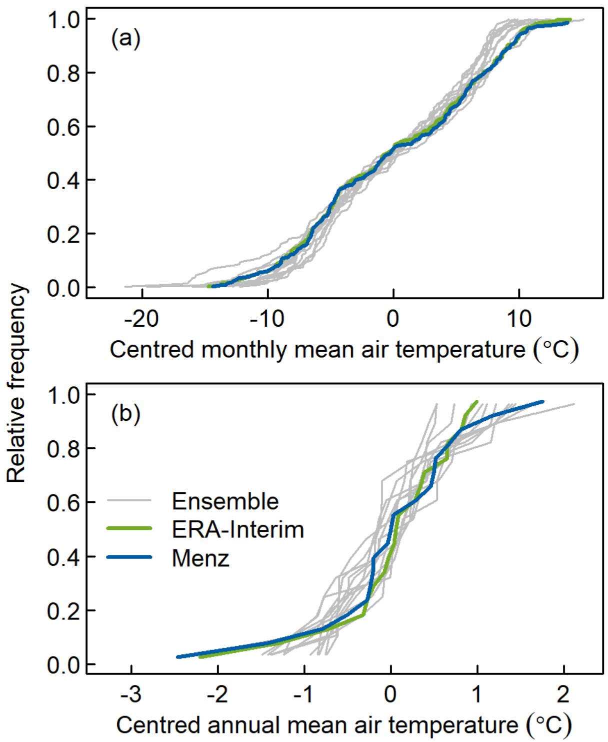

Fig. 3. Cumulative distribution function of centred monthly (a) and annual mean air temperature (b), from 1991 - 2010 data. Grey lines: ensemble, green lines: ERA-Interim, blue lines: Menz station

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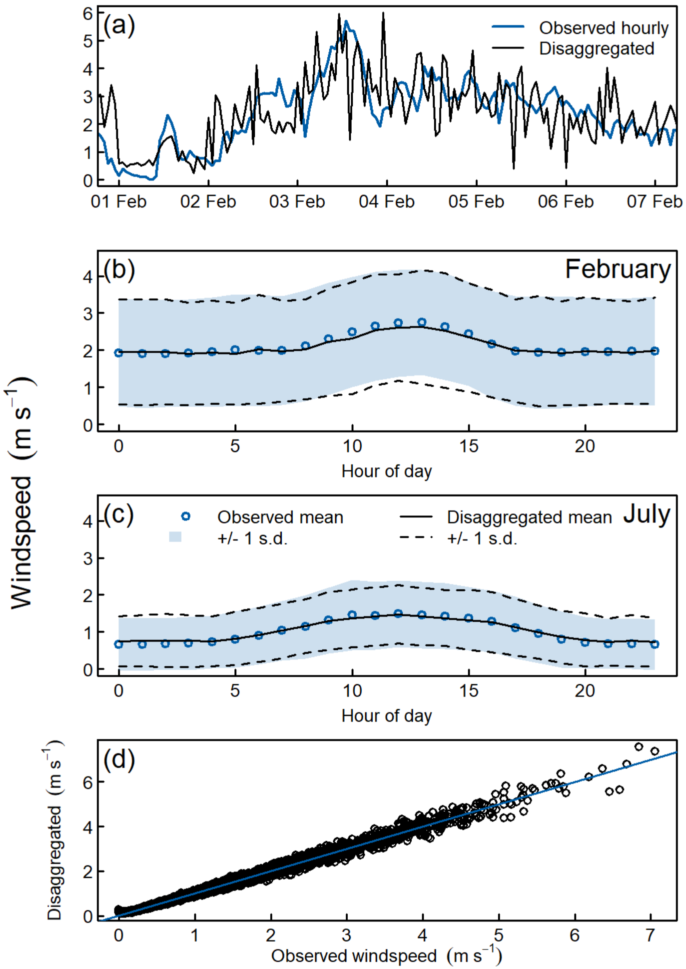

Fig. 4. Validation of algorithm for disaggregating daily windspeeds (black) against Menz observed data (blue). a) data sample, b,c) averaged hourly mean and sd in Feb and July, d) mean (re-aggregated) vs obs