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Hydrology and Earth System Sciences
Discussions

Interactive comment on "A simple lumped model to convert air temperature into surface water temperature in lakes" *by* S. Piccolroaz et al.

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We would like to thank the Referee # 1 for the positive assessment of our manuscript and for providing constructive comments and useful suggestions that we have included in the revised paper.

In the following pages, we respond to each of the Reviewer's comments.

Please notice that pages and lines in this document refer to the original manuscript present in open discussion.

In order to facilitate the review of our response, we include the revised version of the manuscript, in which all modifications are highlighted.

1 General comments

1. When the number of parameters are reduced and the model is applied to just the non-ice periods (NDBC data) it appears to be almost identical in form to the Kettle *et al.*, (2004) model (which is the integrated version). However, the inclusion of a non-dimensionalised mixed layer depth gives the model wider application than the Kettle et al model.

   The 4-parameter version of the model presented in our work and the model developed by Kettle et al. (2004) look similar but they are actually inherently different. Besides the inclusion of the dimensionless mixed layer depth δ, the two models differ also in the other aspects. For example, note that in the simplified version of our model (4-parameter version), the dependence on the solar radiation is neglected (the periodical term of the solar radiation is contained in the parameter p_1, see also point 5 in section "Specific comments"), whereas in Kettle et al. (2004) it is a main forcing term. Furthermore, note that in Kettle et al. (2004) the temperature of surface water depends directly on the solar radiation, whereas in our model (8- and 6- parameter versions) such dependence is expresses in terms of time derivative of surface water temperature (as a direct consequence of the application of the 1D heat equation, see Eq. 2 in the manuscript).

2. Regarding the title I am confused as to what the authors mean by a "lumped model"

   A lumped parameter model is one in which the description of physical systems is done in terms of simplified elements and/or relationships that approximate the behavior of the complete system under certain assumptions and in terms of adjustable (calibrated) parameters usually termed as "lumped". Lumped models differ from distributed parameter systems, in which all dependent variables are functions of time and space.

Example of lumped models are 0D models or black box models in which the system outputs are obtained by transforming the system inputs by means of suitable relationships.

2 Specific comments

1. In the Abstract please mention that: 1. you use the GLUE method, 2. you are only considering long time scales (seasonal, annual and inter-annual) and 3. that the model is an ODE.

   We accepted the Referee's suggestions and modified the abstract as follows:
   page 2698 line 6: *"The model has the form of an ordinary differential equation which accounts for the overall heat exchanges [...]"*
   page 2698 line 15: *"[...] as the only input variable of the model. In particular, the model is suitable to be applied over long time scales (from monthly to interannual), and can be easily used to predict the response of a lake to climate change [...]"*
   page 2698 line 20: *"[...] remaining 9 yr for model validation. The calibration of the model is obtained by using the Generalized Likelihood Uncertainty Estimation (GLUE) methodology, which also allows for a sensitivity analysis of the parameters. The results show [...]"*

2. Section 3: Make it clear that you use the GLERL data in order to obtain winter water surface temperatures. The correspondence between NDBC and GLERL data does not look very good to me (particularly if the annual cycle was removed)....this should be commented upon.

   We thank the Reviewer for the suggestion and we modified the description of GLERL dataset as follows:
   From page 2707, line 24 to page 2708, line 4: *"Concerning GLERL dataset, daily*

temperature maps have been used for the period 1994 to 2011. Data refer to the daily lake average surface water temperature obtained from NOAA polar-orbiting satellite imagery. The series does not present systematic gaps (missing data, see Table 1, are concentrated in the first, warm-up year and hence do not contribute to the evaluation of the model efficiency, see Sect. 4.1), thus providing surface water temperature also in winter, which, on the contrary, is almost completely uncovered by the NDBC dataset. A mismatch between NDBC and GLERL datasets is visible in the rising limb of the annual cycle of temperature (i.e. between April and July, see Fig. 8a), which is likely to be a consequence of the different spatial scales of the two series of data: while the NDBC dataset represents surface water temperature measured nearly at the center of the basin, the GLERL dataset provides values averaged over the whole lake. In the latter case, the spatial variability of surface water temperature (e.g. in spring, lake water heats from the shores towards the offshore deeper zones) is intrinsically included in the estimates, thus determining smoother annual cycles of temperature. Despite this discrepancy, Schwab et al. (1999) compared GLERL data with measurements at some of the NDBC buoys finding an overall good agreement. In particular, for the case of the 45004 - Marquette buoy used in this work, the mean difference between the two datasets for the period 1992 - 1997 is less than $0.28°C$, the root mean square error is $1.10°C$ and the correlation coefficient is 0.96."

- In both Figs 5 and 7 I would like to see another plot below it showing Tw(obs) - Tw(8par) and Tw(obs) - Tw(4 par). Due to the annual cycle it is hard to see how well the model is actually performing without plotting these differences.

  Fig. 1 in this document shows the difference between observed temperatures (GLERL dataset from 1994 to 2005) and numerical results obtained using the 8- and 4-parameters versions of the model. Thin dots represent residuals at a daily scale (i.e. the time step of the model), whereas thick dots show the residuals obtained by filtering measurements and model results with a 30-day moving window. As one would expect, errors at the daily scale are larger than those obtained by filtering the data, but as stated in the manuscript our model is appropriate to investigate temperature evolution over long time scales (seasonal, annual and interannual) rather than reproducing the behavior of the system at daily resolution. Concerning the two different versions of the model the differences are negligible, which is in line with results shown in the original manuscript.

We believe that including the distribution of residuals for all figures in the manuscript (i.e. Figs. 5, 7, 9 and 10 in the original manuscript) could burden the paper making it too long. In order to provide the same information in a more compact way, we included in the revised manuscript a summarizing table listing the values of RMSE - Root Mean Square Error and ME - Mean Error for each simulation and version of the model. This table now also includes the E efficiency indexes, which were previously listed in Table 2 of the original manuscript. The proposed layout of this table is presented in Table 1 at the end of the present document.

In addition, inspired by the comment of the Referee, we included a new figure showing the parity diagram of monthly-averaged surface water temperatures (see Fig. 2 in the present document, which refers to the calibration and validation periods of the GLERL simulation). This plot is intended to further illustrate the correlation between measurements and simulation at a monthly time scale, and provides some additional information about how the model is able to capture the interannual variability of the system.

In order to include all these new elements, the manuscript has been modified as follows (where Figs. 11a and 11b correspond to Figs. 2a and 2b, and Table 3 to Table 1 in this document):
Page 2715, lines 18-24: *"The physically-based, semi-empirical model presented here has been shown to provide an accurate description of surface water temperature of lakes, with high values of Nash-Sutcliffe efficiency index* $E \simeq 0.9$*,*

and a root-mean-square error between observations and simulations of the order of 1°C (see Table 3). This error in prediction capability is comparable to those obtainable using process-based numerical models (e.g. Fang and Stefan, 1996; Stefan et al., 1998), which however have the strong limitation of requiring high resolution weather data and the calibration of numerous internal parameters. The close agreement between measurements and model estimates is further confirmed in Figs. 11a and 11b, which illustrate the parity diagrams for monthly-averaged surface water temperature during the calibration and validation periods of GLERL simulation, respectively. No systematic deviation (bias) is observed and the dispersion along the diagonal does not exhibit significant trends. Both these characteristics are confirmed by the small values of Mean Error (ME) *and Root Mean Square Error* $(RMSE)$ *listed in Table 3. Figures 11a and 11b also illustrate that the model is able to adequately describe interannual fluctuations, as is indicated by the range of variability of monthly-averaged temperatures associated to the coldest (March, blue dots) and warmest (August, red dots) months. This evidence is also confirmed by Figs. 9 and 10, where the model coherently reproduces the occurrence of relatively colder (e.g. 2004) and warmer (e.g. 1998) periods."*

3. Solving an ODE using an explicit Euler scheme is very straightforward but I think it might be worth including the equations in the Appendix to make it easy for others to reproduce this model themselves. Or, if not, it might be worth mentioning in the text that ODE solvers can be easily used in R, matlab etc.

The code is written in Fortran, and no solver packages have been used. Since the explicit Euler scheme is very straightforward, we think that a reference in the text is enough. The text has been modified at page 2708, line 10 as follows:
"The differential Eq. (6) has been solved numerically by using the Euler explicit numerical scheme (see e.g. Butcher, 2003), with a daily time step (concerning

NDBC data, mean daily temperatures have been preliminary calculated from the original data)."

We also modified lines 11-13 at page 2710 as follows:

"Just as a sidenote, 100 000 000 model runs over a period of 18 yr with a daily time step and adopting Intel(R) Xeon(R) CPU X5680 @ 3.33 GHz took around 2 h; the code is written in Fortran 90."

4. In the Discussion the authors mention that their model performs as well as process-based numerical models, but perhaps these models do not require calibration and so are truly predictive? The disadvantage of a data-based model is that it requires water temperature data for calibration.

   In general, process-based models require several information (e.g. air temperature, wind speed, solar radiation, relative humidity, precipitation, cloudiness) to evaluate the heat fluxes at the lake-atmosphere interface (see e.g. Goudsmit et al., 2002; Perroud et al., 2009; Toffolon and Serafini, 2013). These fluxes are needed to solve the complete heat transfer equation, but, unfortunately, meteorological data are often not available, especially over long time periods and at high resolution. Furthermore, not all physical processes can be described into details, thus requiring the use of closure relationships which are primarily based on empirical parameterizations (e.g. bulk transfer coefficient for latent and sensible heat). Usually the range of variability of the main empirical parameters is available in the literature, but still they need to be calibrated for each specific case. In conclusion, despite the assumptions at the basis of this kind of models are certainly less restrictive (process-based models are also to a certain extent data-driven models), they in any case require the calibration of internal parameters. In general, we can affirm that the more rigorous description of natural processes that is achievable using process-based models is counterbalanced by the requirement of much more data in input and by the calibration of numerous internal parameters.

   In order to stress these points, the sentence from line 21 to line 24 at page 2715 has been completed as follows:

   "This error in prediction capability is comparable to those obtainable using process-based numerical models (e.g. Fang and Stefan, 1996; Stefan et al., 1998), which however have the strong limitation of requiring high resolution weather data and the calibration of numerous internal parameters."

5. I would like to see a Table showing the range for each of the p parameters (with units) and a summary of what role the parameter plays in the model is e.g. p8 is related to ice formation and so on. I would also like to see Tr, Dr and delta in this table. Since the meaning of the parameters changes as the number of parameters changes this would also have to be included.

   We agree with the Referee: a clearer description of the parameters is of major concern. We propose to extend the description of the parameters directly in the text in order to give more emphasis to their physical meaning and provide the reader with all the required information for a better comprehension of the model directly at the beginning of the paper. Based upon the formulation of the model, the description of the parameters is only justified for the full (8 parameters) version of the model, whilst in the case of simplified versions (6 and 4 parameters) the parameters lose their physical meaning.

   Furthermore, T_r is deducted from the mixing regime of the lake and from measurements ($T_r = 4^\circ$ for the case of dimictic lakes, $T_r = \min[T_{w,surf}]$ for warm monomictic lakes and $T_r = \max[T_{w,surf}]$ for cold monomictic lakes), as is pointed out at page 2704 lines 7-20. D_r is not explicitly used in the model, but it is implicitly included in the definition of parameters p (page 2705 lines 21-22). δ is a derived quantity: $\delta = D/D_r$ and an explicit expression is provided, which in turns refers to three parameters (p_6, p_7 and p_8). We think the meaning of these quantities are discussed in sufficient detail in the text.

   Concerning the range of variations for each of the p parameters, we modified

Table 2 of the original manuscript including two rows presenting the range of variation of each parameter (see Table 2 of this document).

Furthermore, we modified the text at page 2703 lines 7-10 as follows:
"Note that Eq. (1) accounts for a sinusoidal annual forcing term with amplitude c_1 *and phase* c_2 *(which result from a combination of the seasonal fluctuations of solar radiation and of sensible and latent heat fluxes), an exchange air-water term* $c_4\,(T_a - T_w)$ *(where* c_4 *is a coefficient that is primarily ascribable to a transfer function of sensible heat flux), a constant term* c_3 *and a residual correction* $c_5\,T_w$ *dependent on the water temperature (the last two terms combined together basically account for the contribution of the latent heat flux)."*

6. The numbering of figures is not correct as they should be mentioned in the text in numeric order (e.g Fig. 8a is mentioned before Fig .4)

   If it is in line with the policy of the Journal, we would prefer to leave Figs. 4 and 8a and their citations in the same order as in the current version of the manuscript. Fig. 8a should be mentioned in Page 2708 where NDBC and GLERL data are introduced. At the same time, it is strictly linked to Fig. 8b where the time evolution of the dimensionless epilimnion thickness δ is shown. We could replicate Fig. 8a before Fig. 4, but in this way we would include redundant information.

- First sentence in the Abstract is not very clear and should be rewritten.

  The first sentence of the abstract has been modified as follows:
  Page 2698 Lines 1-3: *"Water temperature in lakes is governed by a complex heat budget, where the estimation of the single fluxes requires the use of several hydro-meteorological variables that are not generally available."*

Table 1. Efficiency index (E), Root Mean Square Error ($RMSE$) and Mean Error (ME) during calibration and validation periods (NDBC, GLERL and GLERL$_{my}$ simulations).

	calibration			validation		
n par.	$E\,[-]$	$RMSE\,[°C]$	$ME\,[°C]$	$E\,[-]$	$RMSE\,[°C]$	$ME\,[°C]$
NDBC (cal: 1985-2002; val: 2003-2011)						
8	0.91	1.40	-0.07	0.90	1.71	-0.01
6	0.91	1.35	-0.09	0.90	1.71	-0.02
4	0.89	1.50	-0.25	0.89	1.77	-0.01
GLERL (cal: 1994-2005; val: 2006-2011)						
8	0.95	1.17	-0.13	0.97	1.02	0.30
6	0.95	1.16	-0.07	0.97	1.01	0.33
4	0.95	1.21	-0.05	0.97	1.08	0.38
GLERL$_{my}$ (cal: mean year 1994-2005; val: 2006-2011)						
8	0.99	0.48	0.06	0.97	1.07	0.23
6	0.99	0.43	0.01	0.97	0.98	0.15
4	0.99	0.47	0.03	0.97	1.11	0.29

3 Technical Corrections

All technical corrections have been accepted.

4 Tables and Figures

Table 2. Estimated model parameters for NDBC, GLERL and GLERL$_{my}$ simulations, and their physical range of variation.

n par.	p_1 $[°C\ d^{-1}]$	p_2 $[-]$	p_3 $[°C\ d^{-1}]$	p_4 $[d^{-1}]$	p_5 $[d^{-1}]$	p_6 $[°C]$	p_7 $[°C]$	p_8 $[°C]$
min	0.00	0.00	-0.12	0.00	-0.02	0	0	0
max	0.33	1.00	0.28	0.01	-0.00	15	15	0.5
				NDBC				
8	1.35x10^{-2}	2.62x10^{-1}	1.47x10^{-3}	6.18x10^{-3}	-3.26x10^{-4}	3.08	14.41	0.31
6	1.56x10^{-2}	2.83x10^{-1}	1.23x10^{-3}	5.95x10^{-3}	-2.36x10^{-4}	3.01	-	-
4	-	-	1.41x10^{-2}	5.87x10^{-3}	-2.23x10^{-3}	2.77	-	-
				GLERL				
8	1.75x10^{-2}	4.67x10^{-1}	2.30x10^{-2}	6.55x10^{-3}	-2.57x10^{-3}	3.50	13.32	0.44
6	2.36x10^{-2}	4.37x10^{-1}	1.93x10^{-2}	5.91x10^{-3}	-2.16x10^{-3}	3.65	-	
4	-	-	2.57x10^{-2}	9.63x10^{-3}	-2.73x10^{-3}	3.54	-	-
				GLERL$_{my}$				
8	1.31x10^{-2}	2.32x10^{-1}	1.55x10^{-2}	8.47x10^{-3}	-1.09x10^{-3}	3.26	11.93	0.45
6	2.01x10^{-2}	2.06x10^{-1}	1.49x10^{-2}	9.69x10^{-3}	-7.58x10^{-4}	3.75	-	-
4	-	-	2.77x10^{-2}	9.16x10^{-3}	-2.87x10^{-3}	3.13	-	-

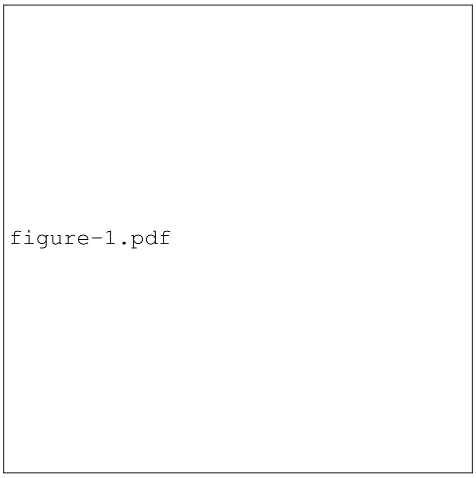

Fig. 1. Residuals of observed (calibration period of the GLERL simulation) vs. modeled surface water temperature obtained using the 8- and 4-parameters versions of the model (black and red dots, respectively). Thin lines refer to a daily scale, whereas thick lines indicate 30-day moving average values.

figure-2.pdf

Fig. 2. Parity diagram for monthly-averaged surface water temperature (8-parameters version of the model): a) calibration and b) validation period of the GLERL simulation. Blue dots refer to March, red dots to August and grey dots to the remaining months of the year.

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