Comment from Referee 1

The authors gratefully acknowledge the time and care given by the referees to their reviews, and the constructive comments made, to which we have paid close attention.

Details of response to comments:

Referee comment

This manuscript addresses the tuning of the FLake model for worldwide lakes, with various adjustments specific to the characteristics of the lakes. This is relevant work, both for evaluation of FLake, and for generalized application of it. However, the presentation is quite poor, with many confusing statements throughout, and poor and often missing use of units of measure. My comments that follow cover both major scientific points and minor editorial points, although the latter class should not be viewed as an exhaustive list of editorial points. The overall sum of problems with this paper leads me to recommend rejection; better presentation would greatly improve this situation.

Author response

We note that the referee acknowledges that relevance of the work presented, and is concerned primarily about presentation, which we take to mean the clarity of what is presented. We have addressed thoroughly the comments made, and have given the entire text another careful review and edit. The additional improvements made during this careful review are listed at the end of the responses.

Referee comment

P. 8548, lines 15-19: "The sensitivity of the summer LSWTs of deeper lakes to changes in the timing of ice-off is demonstrated." This seems to imply a direct causal relationship between the two, whereas reality has both summer LSWT and ice-off dependent on the preceding heat budget. So "correlation" might be a better word than "sensitivity."

Author's Response

This statement is noting that there is a definite relationship between the two; a relationship although related to the heat budget is only evident for deep lakes.

Author's change

The relationship between the changes in the summer LSWTs of deeper lakes and the changes in the timing of ice-off is demonstrated.

Referee comment

Then this goes on to more confusing territory by saying that the summer LSWT response to ice-off is dependent on latitude and depth. The way that I would symbolically represent this statement is "the correlation of [correlation of summer LSWT vs. ice-off day] vs. latitude and depth is 0.5 (R2)". Are you really taking a correlation of a correlation, or

is the second part of the sentence a better representation?: "Lake depth and latitude, explaining 0.5 of the inter-lake variance in summer LSWTs."

Author Response

The full sentence now reads "The modelled summer-LSWT response to changes in ice-off timing is found to be statistically related to lake depth and latitude, which together explain 0.50 ($R^2_{adj,}$ p = 0.001) of the inter-lake variance in summer LSWTs."

Hopefully this is now unambiguous.

This is saying that latitude and depth together can explain half of the changes in JAS LSWT that occurred as a result of delaying the ice-off day.

Author's change

"The modelled summer-LSWT response to changes in ice-off timing is found to be statistically related to lake depth and latitude, which together explain 0.50 ($R^2_{adj,}$ p = 0.001) of the inter-lake variance in summer LSWTs."

Referee comment

P. 8550, line 7: "albedo; snow and ice (alpha)" occurs here and elsewhere. This is a very strange description. Alpha is simply the symbol that stands for albedo, so it should just say "albedo (alpha)". You can certainly make the true statement that albedo is strongly dependent on snow and ice, but the result that you use as an input to FLake is simply albedo.

Author Response

From your interpretation, I realize how confusing this appears. I now refer to albedo as "snow and ice albedo" in every instance throughout the paper. This hopefully assures the reader that I am referring to snow and ice albedo and not the albedo of the liquid water. On P 8557, where I am specifically discussing the tuning of snow and ice albedo, I state that the albedo of water is not tuned remains constant, 0.07.

Author's change

"Snow and ice albedo" replaces "albedo" and "albedo: snow and ice" throughout

"Albedo when discussed throughout this study refers to the albedo of snow and ice. The albedo of water (in liquid phase) is maintained at the default value of 0.07 throughout this study."

Replaces

"Albedo when discussed throughout this study refers to snow and ice albedo."

Referee comment

P. 8550, line 26: Change "seasonally" to "seasonal".

Author Response

Corrected typographical error

Referee comment
My preference is to use a hyphen in "ice-covered" when they are used together to form a compound adjective, such as when they modify "lakes" in "ice-covered lakes". Contrast "Ice covered the lake."

Author Response
Throughout the paper, I have now used hyphens where two words are put together to make a compound adjective.

Author's changes
"Seasonally ice covered" now reads "Seasonally ice-covered",
"post tuning" now reads "post-tuning" and
"LSWT regulating properties" now reads "LSWT-regulating properties"
Note "non-seasonally ice covered lakes" are now referred to as "non-ice covered lakes"

Referee comment
P. 8552, line 13, and elsewhere: GMD might have an editorial policy on this. Although some German-language sources might have this name spelled "Mironow", every instance I found on Google mentioning this paper, admittedly all English-language sources, has it spelled "Mironov", and you have it that way on p. 8574, lines 8 and 11.

Author's changes
Corrected, this should be "Mironov" throughout

Referee comment
P. 8553: The variables "c_relax_C", "fetch", and "latitude" are formatted here as a list of definitions. This would make more sense visually if each of these key words were italicized, and a colon works better than a semi-colon to separate a term from its definition.

Author's changes
"c_relax_C", "fetch" and "latitude" now Italicized with colon

Referee comment
P. 8553, line 1: I am a stickler for proper use of units, and this is the first of several comments on this topic. This line says that c_relax_C is a relaxation time scale. This implies that its units are time, such as seconds or days. Then you proceed to mention values without units, and imply that larger values of c_relax_C indicate more vigorous vertical mixing of water, meaning that a larger value of c_relax_C means a shorter relaxation time. I think its units are inverse time.

Author Response
c_relax_C is a dimensionless constant used in the relaxation equation for the shape factor with respect to the temperature profile in the thermocline. I've updated the description

Author's changes
"*c_relax_C*: a dimensionless constant used in the relaxation equation for the shape factor with respect to the temperature profile in the thermocline."

Replaces
"c_relax_C; is a relaxation time scale for the temperature profile in the thermocline."

Referee comment

P. 8553, eq. 1: Even though not directly stated, we've established above that fetch has units of length (maybe km), so this equation should show this explicitly. Is 39.9 in units of km? What are the units of area, and how does its coefficient convert it back into the same units of length? Including units is crucial for the reader to be able to address the question, "Does this equation make sense?"

Author Response
In this equation, fetch is calculated in km (the length and breadth of the lakes are in km, as it the area and the constant). The co-efficient is determined from the relationship between the calculated fetch (square root of the product of lake length and breadth measurements) and the surface area of the 205 lakes with length and breadth measurements.
I've now included UOM.

Author's changes
"fetch = 39.9 km + 0.00781 area km"

replaces

"fetch = 39.9 + 0.00781 area"

Referee comment

P. 8553, line 15: The name "Doll" should have an umlaut over the "o".

Author Response
umlaut now included

Author's changes
"Döll" replaces "Doll"

Referee comment

P. 8554, line 2: Units should be W m-2 (with superscript) rather than W m2.

Author Response
Corrected typographical error

Referee comment
P. 8554, line 15: This shows units of m for fetch. Are you really dealing with water bodies with fetch < 16 m? That's a very small water body.

Author Response
Corrected typographical error, this should read "km" not "m".
Also corrected is the intended use of Hsu's equation – it is applicable to wind speeds over sea surfaces.

Author's changes
"For adjusting wind speeds over land (measured in m/s), to wind speeds over sea surfaces, Hsu (1988) recommends the scaling shown in Eq. (4). For bodies of water with fetch < 16 km a scaling of 1.2 is considered reasonable (Resio et al., 2008)."

replacing

"For water bodies with fetches >16 m, Hsu (1988) recommends the scaling shown in Equation 4. For bodies of water with fetch < 16 m a scaling of 1.2 is considered reasonable (Resio et al., 2008)."

Referee comment
P. 8554, eq. 2 needs units.

Author Response
units in m/s

Author's changes

"Uwater = 1.62 m/s + 1.17 Uland

Where Uwater = wind speed over water (m/s), and
Uland = wind speed over land (m/s)"

Replaces
"Uwater = 1.62 m + 1.17 Uland"

Referee comment
P. 8555, eq. 3: This strongly implies that kappa has units of m-1 (as does eq. 4), so the intercept 0.07 in this equation should have those same units. On the next line, it is ambiguous whether units of m refer to Secchi disk depth or inverse Secchi disk depth;

it is much more straightforward to say “where S = Secchi disk depth (m)”.

Author Response

Yes correct, *ksd* is in units of m-1 for both eq 3 and eq 4, as is the intercept in eq 3. This is now clarified.

Author’s changes

“The light extinction coefficients values for the untuned model trial are derived from Secchi disk depth, *ksd* (m-1)”

replaces

“The light extinction coefficients values for the untuned model trial are derived from Secchi disk depth (ksd)”

Agreed, to avoid unnecessary forms of the same term, I now refer to all Secchi disk depth measurements (S) in meters and have updated the equations to reflect this.

P. 8555, line 19 (eq 3):

κsd = (0.757/S) + 0.07m-1

replaces

κsd = 0.757*S-1 + 0.07

P. 8555, line 20

where S = Secchi disk depth (m)

replaces

where S-1 = inverse Secchi disk depth (m)

P. 8556, line 2 (eq 4)

κsd =1.7/ S

replaces

Ksd = 1.7 / Secchi disk depth

Referee comment

P. 8559, eq. 5: It is necessary to make it really straightforward what is meant by this operation. You’re calculating varjas for whole groups of lakes, right? So N isn’t just the number of years, but the sum of the number of years over all of the lakes. And xbar is the mean across both years and lakes. Whether I’m right or wrong about this, it needs clarification.

Author Response
varjas is calculated for each lake, so for a given lake, N is the number of years with LSWT observations and x bar is the mean across all years.

N and x bar are now explained in equation

Author's changes

$$var_{jas} = \sum \left(x_i^{obs\_jas} - \bar{x} \right)^2 / (N - 1) \qquad (5)$$

where $^{obs\_jas}$ = observed mean JAS LSWT
$\bar{x}$ = mean across all years
N = number of years with JAS LSWTs

Replaces

$$var_{jas} = \sum \left(x_i^{obs\_jas} - \bar{x} \right)^2 / (N - 1) \qquad (5)$$

"where obs_jas = observed JAS LSWT "

Referee comment
P. 8559, line 7: You have interjas in the same definition format as on p. 8553, so it should be set off by a paragraph break, italics, and followed by a colon.

Author Response
Corrected

Referee comment
P. 8559, line 14: Then you need to clarify what "max" and "min" mean. Are these the monthly mean values that happen to be warmer (cooler) than any other month of the year. If most years have August with the warmest LSWT, but one has the warmest water in September, do I insert the September value for that year, or is do I always use the same month, with the highest mean value?

Author Response
Yes these are monthly mean values that happen to be warmer (cooler) than any other month of the year. These LSWTs are not tied to a particular calendar month. The minimum LSWT refers to the month in which the minimum LSWT occurs, be it August or September or any other month. The same applies to the maximum LSWT. I have now included a description of the terms used in the equations (obs_min, mod_min, obs_max and mod_max) on P. 8559, line 14.

Author's changes

“where *obs_min* (and *mod_min*) = mean observed LSWT (and modelled LSWT) in the month where the minimum LSWT occurs, and
where *obs_max* (and *mod_max*) = mean observed LSWT (and modelled LSWT) in the month where the maximum LSWT occurs”

Referee comment

P. 8559 and elsewhere: When you use the form varjas(K2), it seems to mean “varjas in units of K squared”. On the other hand, interjas(R2adj) seems to mean “interjas, which can be thought of as being like a correlation coefficient, but with adjustments for the number of predictor variables”. Both of these are at odds with what I think of at the standard form f(x), “f as a function of x”, so this becomes quite confusion and needs to be explained.

Author Response

Correct, varjas, varmin and varmax are in units of kelvin squared. varjas measures the observed JAS LSWT variance for each seasonally ice-covered lake. varmin (and varmax) measure the observed variance in the mean LSWT value for the month of minimum (and maximum) LSWT, for each non-ice covered lake. interjas, intermin and intermax measure the respective fraction (R^2adj) of the observed variance that is accounted for in the tuned model for each lake. This is reworded in section 2.4.3.

Author change (section 2.4.3)

“For non-ice covered lakes, the observed variance (K^2) over the length of the tuning period is determined using var_{min} (and var_{max}): the mean LSWT for the month in which the minimum (and maximum) LSWT is observed. For seasonally ice-covered lakes, the variance is determined using var_{jas}: the variance in the observed mean JAS LSWT over the length of the tuning period. The fraction of these observed LSWT variances accounted for in the tuned model are quantified, $inter_{min}$, $inter_{max}$ and $inter_{jas}$ (R^2_{adj}), respectively.”

Referee comment

P. 8563, lines 14-15: Are you saying that water density is lower because of atmospheric pressure? Lakes and oceans add about 1 atmosphere of pressure for each 10 m of depth, but this has a rather minimal effect on water density. Then I don’t see how lower water density inhibits heat transfer, especially if you balance the effects of density on effective thermal conductivity (eddy diffusivity) and on thermal capacity.

Author Response

I’m not referring to depth here. I was trying to say that at higher altitudes the atmosphere is rarified, so the natural convective and thermal heat transfer processes are less effective. Referee 3 has also suggested that effect was negligible. I have removed this and have now stated that altitude is considered through the altitude associated with meteorological data grid points.

Author’s change

“Although the density of freshwater in *FLake* is determined at sea level (normal atmospheric pressure) (Mironov, 2008) and the altitude of lakes are not directly considered in *FLake*, lake altitude (ranging from -12 to 5000 m a.s.l., over the 246 lakes) is considered indirectly through the altitude of the meteorological forcing data (ERA) at the lake centre co-ordinates. "

Referee comment

P. 8564, line 27: When it says p=0.000 here and on the next page, is that a typo, or does it mean that it's less than 0.0005?

Author Response

Yes, it also means that the p value is less 0.0005. The p-values are reported to 3 decimal places throughout – I've changed "p = 0.000" to "p < 0.0005" for correctness.

Referee comment

P. 8566, lines 18-20: This is a similar problem to some of the wording in the abstract. I think you did one correlation of depth and latitude to the delay in 1 deg warming day due to increased albedo, and another of depth and latitude to the decrease in JAS LSWT. If this is correct, then change "between" to "in" and add another "in" before "the JAS LSWT…." If this is incorrect, then what you actually did needs more careful explanation.

Author Response

You're right, this is very confusing, it was worded incorrectly. The correlation is drawn between the JAS LSWT decrease (caused by the change in the 1 °C warming day) and latitude & depth.
I've re-worded this section

Author's change

"A higher albedo (*α2*, Table 2) delays the 1 ºC warming day by 27 ± 12.6 days and decreases the mean JAS LSWT mean difference by ~50%, to 0.98 + 2.51 ºC, across the 21 lakes. There is no correlation between the modelled JAS LSWT decrease and the length of the delay in the 1 ºC warming day (due to the increased snow and ice albedo) over the 21 lakes. This indicates that the JAS LSWT of the lakes do not respond in the same manner to changes in the 1 ºC warming day. Lake depth and latitude were found to account for much of the modelled variance in the JAS LSWT decrease (caused by the changes in the 1 ºC warming day). Across the 21 lakes together (using stepwise regression), lake depth and latitude account for 0.50 (R^2_{adj}, p = 0.001) of the variance in the JAS LSWT decrease. Separately, depth accounts for 0.35 (p = 0.003) and latitude for 0.26 (p = 0.01) of the variance."

Referee comment

P. 8566, line 26: "….as a result of" implies a direct cause-effect relationship. I suspect that the delay in 1 deg warming day didn't actually cause the LSWT decrease, but that they were associated because albedo caused both. The same statement of causality also occurs in the following sentence, as well as p. 8567, lines 8-11.

Author Response

Recalling that the albedo in question is that of snow & ice (not the liquid phase), there appears to be a causal chain: higher albedo delays the ice-off day, allowing less time for the water to warm, such that for those cases where the summer peak temperature is not close to equilibrium with the summer environment, e.g. deeper lakes, a lower JAS LSWT results.

Referee comment

P. 8567, line 23: Remove "of".

Author Response

Corrected

Referee comment

P. 8567, line 27: Pull "lakes" outside of the parentheses.

Author Response

Corrected

Referee comment

P. 8568, line 12: Start a new sentence at "Therefore".

Author's change

Updated as suggested by referee 3

"There is a snow cover module with *FLake* which is not operational in this version of the model; therefore the insulating effect that snow has on the underlying ice is not modelled."

Referee comment

P. 8568, line 17: When you say "more timely" here, I think it means "less biased in time", which would be a better description.

Author Response

I haven't used the term "less bias in time" as referee 3 commented that bias indicated that the observed LSWTs were the true LSWTs, and so suggested to use "mean differences" instead of bias.

Author's change

"As shown in the tuning process, a higher albedo results in a later 1 °C warming day (reducing the mean difference between the modelled and observed LSWTs)"

Also changed in section 3

"The higher wind speed scaling (*u3*) causes earlier cooling and later warming (reducing the 1 °C cooling day and 1 °C warming day mean differences), lengthening the ice cover period"

Referee comment

P. 8568, line 26: Change “being” to “been”.

Author Response
Corrected

Referee comment
P. 8569, lines 15-16: The units should be kg per cubic meter, so I think the exponent of -3 belongs to the number 10, not the unit of kg, and the exponent for m should be -3, not 3.

Author Response
Corrected

Referee comment
P. 8569, line 19: “….buffering effect against wind” is vague. Against wind causing what? Heat flux through the thermocline or surface?

Author Response
The density gradient of the thermocline may act as a buffer against wind and heat flux – this is reworded

Author’s change
“It is possible that the large density difference between the lake surface at maximum LSWT and the hypolimnion in high latitude lakes during the stratification period, may produce a buffer against wind induced mixing and therefore lessen the heat flux through the thermocline.”

Referee comment
P 8569, line 20: “Purports to” doesn’t make sense here. Possibly substitute “is set to”.

Author change (P 8569, line 25)
Reworded “Al Although the density differences between the two layers are considered in *FLake*, the model is forced with over land wind speed measurements.“

Referee comment
P. 8570, line 5: I think the idea is that you have done a generalized tuning that can apply across all lakes, with dependence on the lakes’ properties. Therefore, “without needing to tune the model” should have appended “for each lake”.

Author’s change
“The optimal LSWT-regulating properties of the 244 lakes provide a guide to improving the LSWT modelling in *FLake* for other lakes, without having to tune the model for each lake separately.”

Referee comment

P. 8570, line 20: This is where I've bothered to note that you missed capitalizing the "L" in "FLake", but it occurs elsewhere, too. My autocorrection just tried to overrule me on doing it this way.

Author's change
P. 8570, line 21
"As FLake" replaces "As Flake"

P. 8578, Table 1 header
"FLake input" replaces "Flake input"

P. 8578, Table 1, 1st row
"FLake input" replaces "Flake input"

P8605, Figure 17 caption (3rd line)
"FLake lake model" replaces "Flake lake model"

Referee comment

P. 8571, line 5: To make it clear that 21 m is part of the first clause of the sentence, and 13 m is part of the second part, follow the number 21 with the unit of m, then a comma.

Author Response
I've changed this section due to comment from referee 3 - only one average depth reported.

Author's change
"Across all lakes, 57% were tuned to light extinction coefficient values of κ_{d4} or κ_{d5}. These lakes are globally distributed and have a wide range of mean depths (1-138 m) with an average mean depth of 16 m."

Replaces
"The average depth of lakes tuned to κd4 is 21 and 13m for lakes tuned to κd5."

ADDITIONAL IMPROVEMENTS MADE TO PAPER AT SUGGESTION OF FIRST REFEREE

Author's change: P8548, line 4-7

"The model, which was tuned using only 3 lake properties (lake depth, snow and ice albedo and light extinction coefficient), substantially improves the measured mean differences in various features of the LSWT annual cycle, including the LSWTs of saline and high altitude lakes, when compared to the observed LSWTs."

Replaces

"The model, tuned using only 3 lake properties; lake depth, albedo (snow and ice) and light extinction co-efficient, substantially improves the measured biases in various features of the LSWT annual cycle, including the LSWTs of saline and high altitude lakes"

Author's change: P8548, line 7-14

"Lakes whose lake-mean LSWT persists below 1 °C for part of the annual cycle are considered to be 'seasonally ice-covered'. For trial seasonally ice-covered lakes (21 lakes), the daily mean and standard deviation (2σ) of absolute differences (MAD) between the modelled and observed LSWTs, are reduced from 3.07 ± 2.25 °C to 0.84 ± 0.51 °C by tuning the model."

Replaces

"The daily mean absolute differences (MAD) and the spread of differences (±2 standard deviations) across the trial seasonally ice covered lakes (lakes with a lake-mean LSWT remaining below 1 °C for part of the annual cycle) is reduced from 3.01 ± 2.25 °C (pre-tuning) to 0.84 ± 0.51 °C (post-tuning). For non- seasonally ice-covered trial lakes (lakes with a lake-mean LSWT remaining above 1 °C throughout its annual cycle), the … "

Author's change: P8548, line 15-18

"The relationship between the changes in the summer LSWTs of deeper lakes and the changes in the timing of ice-off is demonstrated. The modelled summer-LSWT response to changes in ice-off timing is found to be statistically related to lake depth and latitude, which together explain 0.50 ($R^2_{adj,}$ p = 0.001) of the inter-lake variance in summer LSWTs."

Replaces

"The sensitivity of the summer LSWTs of deeper lakes to changes in the timing of ice-off is demonstrated. The modelled summer LSWT response to changes in ice-off timing is found to be strongly affected by lake depth and latitude, explaining 0.50 (R2adj, p = 0.001) of the inter-lake variance in summer LSWTs."

Author's change: P8548, line 19-21

"Lake characteristic information (snow and ice albedo and light extinction coefficient) is not available for many lakes. The approach taken to tune the model, bypasses the need to acquire detailed lake characteristic values."

replaces

The tuning approach undertaken in this study, overcomes the obstacle of the lack of available lake characteristic information (snow and ice albedo and light extinction co-efficient) for individual lakes.

Author's change: P8548, line 22-23

"Furthermore, the tuned values for lake depth, snow and ice albedo and light extinction coefficient for the 244 lakes provide some guidance on improving *FLake* LSWT modelling."

Replaces

"Furthermore, the tuned values for lake depth, snow and ice albedo and light extinction co-efficient for the 244 lakes provide guidance for improving LSWTs modelling in FLake."

Author's change: P8550 line 6

"Through this preliminary work, the lake-specific properties which exerted the strongest effect on the modelled LSWTs were selected. These properties are lake depth (d), snow and ice albedo (α) and light extinction coefficient (κ)."

Replaces

"Through preliminary model trials, three properties; lake depth (d), albedo; snow and ice (α) and light extinction coefficient (κ) are shown to greatly influence the modelled LSWT cycle."

Author's change: P8551 line 6

2.1 Data: ARC-Lake observed LSWTs

replaces

2.1 Data; ARC-Lake observed LSWTs

Author's change: P8551 – lines 7-12

"LSWT observations from ARC-Lake are used to tune the model. These cover 246 globally distributed large lakes, principally those with surface area >500km^2 (Herdendorf, 1982; Lehner and Döll, 2004) but also including 28 globally distributed smaller lakes, the smallest of which is 100 km^2 (Lake Vesijarvi). The LSWTs are generated from three Along-Track Scanning Radiometers (ATSRs), from 1991–2011 (MacCallum and Merchant, 2012).

Replaces

“The ARC-Lake LSWT observations for 246 globally distributed large lakes, principally those with surface area >500km2 (Herdendorf, 1982; Lehner and Doll, 2004) but includes 28 globally distributed smaller lakes, the smallest of which is 100km2 (Lake Vesijarvi) are used to tune the model. These LSWTs are generated from three Along-Track Scanning Radiometers (ATSRs), from 1991–2011 (MacCallum and Merchant, 2012).”

Author’s change: P8551 – lines 14-26

“The ARC-Lake observations have been shown to compare well with in situ LSWT data. Validation of the observations was performed through a match-up data set of in situ temperature data consisting of 52 observation locations covering 18 of the lakes (MacCallum and Merchant, 2012). Furthermore, the timing of ice-on and ice-off events is observed to be consistent with in situ measurements. This is demonstrated through analysis of the average (over the period of ATSR observations) days of the year on which the lake-mean LSWT drops below 1 $^{\circ}$C and rises above 1 $^{\circ}$C. Layden et al. (2015) define these as the 1 $^{\circ}$C cooling and 1 $^{\circ}$C warming days respectively, and observe good consistency with in situ measurements of ice-on and ice-off days for 21 Eurasian and North American lakes. Layden et al. (2015) also demonstrate the integrity of the ARC-Lake LSWTs on a global scale, through the strong relationship the observed LSWTs have with meteorological data (air temperature and solar radiation) and geographical features (latitude and altitude). On this basis, the ARC-Lake LSWT observations are considered reliable and suitable for use in this tuning study.”

Replaces

“The ARC-Lake observations have been shown to compare well with in situ LSWT data. Validation of the observations was performed through a match-up data set of in situ temperature data consisting of 52 observation locations covering 18 of the lakes (MacCallum and Merchant, 2012). Furthermore, the 1 ^{o}C cooling and warming day, which is defined as the day of the year on which the average (over the period of observations) lake-mean LSWT drops to below 1 ^{o}C (1 ^{o}C cooling day) and rises to above 1 ^{o}C (1 ^{o}C warming day), show a good consistency with in situ measurements of ice-on and ice-off days for 21 Eurasian and North American lakes (Layden et al., 2015). Layden et al. (2015) also demonstrates the integrity of the ARC-Lake LSWTs on a global scale, through the strong relationship between the observed LSWTs and meteorological data (features of air temperature and solar radiation) and geographical features (latitude and altitude). On this basis, the ARC-Lake LSWTs are considered reliable and suitable for use in this tuning study.”

Author’s change: P8552 – line 16

…and ice models: meteorological forcing data…

Replaces

…and ice models; meteorological forcing data…

Author’s change: P8552 – lines 23-25

“As outlined in the introduction, optimisation of LSWT-regulating properties (lake depth (d), snow and ice albedo (α) and light extinction coefficient (κ)), can greatly improve the LSWTs produced in *FLake*.”

Replaces

“As outlined in the introduction, optimisation of LSWT regulating properties; lake depth (d), albedo; snow and ice (α) and light extinction coefficient (κ), can greatly improve the LSWTs produced in FLake.”

Author’s change: P8554 – lines 10-12
“Mean daily values of the following parameters are used to force the model (shown in Table 1): shortwave solar downward radiation (SSRD), air temperature and vapour pressure at 2m, wind speed, and total cloud cover (TCC).”

Replaces

“Shortwave solar downward radiation (SSRD), air temperature and vapour pressure at 2m, wind speed and total cloud cover, in their mean daily values, as shown in Table 1 are used to force the model.”

Author’s change: P8555 – lines 20-22
“Of the 5 studies, this formula produces the lowest (most transparent) κ values, potentially more representative of open water conditions of large lakes, and is therefore used in this study for lakes with Secchi disk depths of 2-10 m.”

Replaces

“Of the 5 studies, this formula produces the lowest (most transparent) κ values, and possibly more likely to represent open water conditions of large lakes and is therefore used in this study.”

Author’s change: P8556 – lines 7
“attenuation process of ocean water and its changes with turbidity (Jerlov, 1976) is applied.”

Replaces

“attenuation process of oceans and its changes with turbidity (Jerlov, 1976) is applied.”

Author’s change: P8556 – lines 10
“The spectre for these 10 ocean types are divided (in fractions of 0.18, 0.54, 0.28) into three wavelengths: 375, 475 and 700nm, respectively.”

Replaces

“The spectre for these 10 ocean types are divided (0.18, 0.54, 0.28) into three wavelengths; 375, 475 and 700nm, respectively.”

Author’s change: P8558 – lines 23-25 and P8559 – line 1

“For non-ice covered lakes, the observed variance (K^2) over the length of the tuning period is determined using var_{min} (and var_{max}): the mean LSWT for the month in which the minimum (and maximum) LSWT is observed. For seasonally ice-covered lakes, the variance is determined using var_{jas}: the variance in the observed mean JAS LSWT over the length of the tuning period.”

Replaces

“For the observed LSWTs, over the length of the tuning period, the variance (K2) in the month of minimum and maximum LSWT for non-seasonally ice covered lakes (varmin and varmax) and in the JAS LSWT for seasonally ice-covered lakes (varjas) is determined.”

Author’s change: P8560 – lines 23-25
For the remainder of the trials (tuned), for non-ice covered lakes, wind speed scaling, *u1*, was applied to lakes at latitudes < 35 °N/S and *u3* to lakes at latitudes > 35 °N/S”

Replaces

“For the remainder of the trials (tuned), wind speed scaling u1, was applied to lakes at latitudes < 35 °N/S and u3 to lakes at latitudes > 35 °N/S for non-seasonally ice covered lakes.”

Author’s change: P8561 – lines 5-9
“These results demonstrate that the tuning process with the applied wind speed scalings can provide significant improvements on the untuned model: run using the lake mean depth, light extinction coefficients derived from Secchi disk depth (as shown in Sect. 2.3.1) and the model default albedo (seasonally ice-covered lakes only).”

Replaces

“These results demonstrate that the untuned model, run using the lake mean depth, light extinction coefficients derived from Secchi disk depth (as shown in Sect. 2.3.1) and default the model default albedo (seasonally ice covered lakes only) can be greatly improved by the tuning process with the applied wind speed scalings.”

Author’s change: P8561 – lines 14
MAD of 1.11 ± 0.56 ^{o}C
Replaces
MAD of 1.11 + 0.56 ^{o}C

Author's change: P8561 – lines 14-15

" Across the 160 lakes, an average MAD of below 1 °C was achieved (0.80 ± 0.56 °C, Table 5)."

Replaces

"Across the 160 lakes, an average MAD (0.80 ± 0.56 ^{o}C, Table 5), of below 1 ^{o}C was achieved."

Author's change: P8561 – lines 16-18

"For non-ice covered lakes, an average MAD of below 1 °C is again achieved (0.96 ± 0.66 °C) when 84 of the 86 lakes are considered (Table 5). However, the remaining two lakes yielding highly unsatisfactory results."

Replaces

"For non-seasonally ice covered lakes, the average daily MAD result for 84 of the 86 lakes is 0.96 ^{o}C, with a spread of differences of ±0.66 ^{o}C (2), Table 5, achieving an average MAD of below 1 ^{o}C. Two of the 86 lakes yield highly unsatisfactory results."

Author's change: P8561 – lines 23-24

"For the remaining 25 lakes, the tuned metrics (not shown in Table 6) are comparatively poor: the 1 °C cooling day was 14 days too early and/or the JAS LSWT mean difference value was ≥ 2 °C."

Replaces

"For the remaining 25 lakes, the tuned metrics are comparatively poor; the 1 ^{o}C cooling day was 14 days too early and/or the JAS LSWT value was ≥ 2 ^{o}C."

Author's change: P8562 – lines 5-8

"This indicates that the these lakes require a greater modelled depth to increase the heat capacity - postponing the 1 ^{o}C cooling day - and lower transparency values (higher κd), causing less heat to be retained in the surface and lowering the JAS LSWT."

Replaces

"This indicates that the these lakes require a greater modelled depth to increase the heat capacity, postponing the 1 ^{o}C cooling day and lower transparency values (higher κd) causing less heat to be retained in the surface, decreasing the JAS LSWT."

Author's change: P8562 – lines 17-19

"Poor tuning results are observed for two of the 86 lakes (Lake Viedma and the Dead Sea). This is most likely due to differences between the altitude of the ERA T2 air temperature (geopotential height) and the lake altitude."

Replaces

“For 2 of the 86 lakes, Lake Viedma and the Dead Sea, the difference between the altitude of the ERA T2 air temperature (geopotential height) and the lake altitude is the most possible cause for poor tuning results.”

Author’s change: P8562 – lines 19-23

“Lake Viedma, an Argentinian freshwater lake of unknown depth, yielded a daily MAD of 3.1 °C. The Dead Sea, a deep and highly saline lake (340 g L^{-1}) located in Asia at 404 m below sea level, yielded a daily MAD of 4.1 °C.”

Replaces

“Lake Viedma, an Argentinian freshwater lake of unknown depth yielded a daily MAD of 3.1 ^{o}C and The Dead Sea, a deep and highly saline lake (340 g L-1) located in Asia at 404 m below sea level yielded a daily MAD of 4.1 ^{o}C.”

Author’s change: P8562 – lines 23-24

“For the Dead Sea, a temperature difference (in the month of maximum temperature) between the observed LSWT (33 °C) and ERA T2 air temperature (25 °C), results in a negative modelled mean difference of 6.3 °C in LSWT for this month.”

Replaces

“For the Dead Sea, a difference in the month of maximum temperature between the observed LSWT (33 ^{o}C) and ERA T2 air temperature (25 ^{o}C), results in a negative modelled bias of 6.3 ^{o}C in the month of maximum LSWT.”

Author’s change: P8563 – lines 6-8

“This difference can be, at least, partially explained by the difference in altitude (> 500 m a.s.l.) between the altitude of Lake Viedma (297 m a.s.l.) and the altitude of meteorological data (825 m a.s.l.) at the lake centre co-ordinates.”

Replaces

“This bias can be at least, partially explained by the difference in altitude of > 500 m a.s.l., between the altitude of Lake Viedma (297 m a.s.l.) and the altitude of meteorological data at the lake centre co-ordinates of 825 m a.s.l.”

Author’s change: P8565 – lines 20-22

“The mean metric results and the spread of differences across the 135 seasonally ice-covered lakes are highly comparable across all 3 years of the tuned and untuned periods, with marginally better MAD metrics observed for the untuned period.”

Replaces

“The mean metric results and the spread of differences across the 135 seasonally ice covered lakes for the tuned and untuned period are highly comparable across all 3 years, showing marginally better MAD metrics for the untuned period.”

Author’s change: P8565 – lines 25-27

“For the other 3 metrics for the 25 shallow lakes, the untuned year has a lower spread of differences across lakes than for 2010. Marginal improvements are also seen in the JAS LSWT and 1 °C cooling day.”

Replaces

“For the other 3 metrics for the 25 shallow lakes, the untuned year has a lower spread of differences across lakes than for 2010 and a marginally better JAS LSWT and 1 °C cooling day.”

Author’s change: P8566 – lines 12-14

“Through the trial work, the effect of the timing of the 1 °C warming day (indicative of ice-off) on the JAS LSWT and on the timing 1 °C cooling day (indicative of ice-on) is demonstrated, for deep high latitude or very deep seasonally ice-covered lakes.”

Replaces

“Through the trial work, the effect of the timing of the 1 °C warming day (indicative of ice-off) on the JAS LSWT and on the timing 1 °C cooling day (indicative of ice-on) of deep high latitude or very deep seasonally ice covered trial lakes is demonstrated.”

Author’s change: P8567 – line 16

“resulted in the 1 °C cooling day occurring 3.4 days earlier.”

Replaces

“resulted in an earlier 1 °C cooling day of 3.4 days.”

Author’s change: P8567 – lines 17-18

“For Great Bear (72 m), the JAS LSWT decrease of 3.40 °C causes an earlier 1 °C cooling day, by 7.6 days.”

Replaces

“For Great Bear (72 m), the JAS LSWT decrease of 3.40 °C causes an earlier 1 °C cooling day of 7.6 days.”

Author’s change: P8568 – lines 7-10

“For example, Lake Nipigion and Lake Manitoba, both located in Canada (50 °N and 51 °N) and at similar altitudes (283 m a.s.l. and 247 m a.s.l) have considerably different depths, 55 m and 12 m respectively. Significant differences are observed in JAS LSWT for these lakes, the deeper lake having an average JAS LSWT 4.4 °C lower than that of the shallower lake (15.4 °C compared to 19.8 °C).”

Replaces

“For example, Lake Nipigion, located in Canada at 50 °N and at 283 m a.s.l., has a mean depth of 55 m and an average JAS LSWT of 4.4 °C lower (15.4 °C) than that of Lake Manitoba (19.8 °C), also located in Canada (at 51 °N and 247 m a.s.l.), but with a mean depth of only 12 m.”

Author’s change: P8569 – lines 3-6

“Although changes in other factors affect hypolimnion temperature, such as influx of cooler water and geothermal heating, the monthly minimum LSWTs from satellites can offer a good indication of hypolimnion temperature; useful in cases where this otherwise can not be or aren’t observed directly.”

Replaces

“Although, changes in other factors affect hypolimnion temperature, such as influx of cooler water and geothermal heating, the monthly minimum LSWTs from satellite can offer a good indication of hypolimnion temperature in cases where this otherwise can not be or isn’t observed directly.”

Author’s change: P8569 – lines 8-11

“The trials showed that while non-ice covered lakes at latitudes < 35 °N/S required no wind speed scaling ($u1$), the largest wind speed scaling ($u3$) improved LSWTs for non-ice covered lakes at latitudes > 35 °N/S and all seasonally ice-covered lakes, as outlined in Sect. 3.£

Replaces

“The trials showed that while non-seasonally ice covered lakes at latitudes < 35 °N/S required no wind speed scaling (u1), non-seasonally ice covered lakes at latitudes > 35 °N/S and all seasonally ice covered lakes produced more representative LSWTs using the largest wind speed scaling (u3) as outlined in Sect. 2.2.3.”

Author’s change: P8571 – line 10

“Scarce”

Replaces

“scare”

Author's change: P8571 – lines 13-16

"In the first model run, the average κ_{sd} value (derived from Secchi disk depth data) of the trial lakes of each lake type is applied to all lakes of corresponding type. For the 21 seasonally ice-covered trial lakes, Ksd = 0.82; for the 14 non-ice covered trial lakes, κ_{sd} = 1.46."

Replaces

"In the first model run, the average κ_{sd} (derived from Secchi disk depth data) of the 21 seasonally ice covered trial lakes, 0.82, is applied to all seasonally ice covered lakes and the average κ_{sd} of the 14 trial non-seasonally ice covered lakes, 1.46, is applied to all non-seasonally ice covered lakes."

P8571 – lines 18-19

"For both model runs the default albedo and the mean depth are applied, while all other model parameters are kept the same."

Replaces

"For both model runs the default albedo and the mean depth are applied and all other model parameters are kept the same."

P8572 – lines 13-18

"The 1-dimensional freshwater lake model, *FLake*, was successfully tuned for 244 globally distributed large lakes (including saline and high altitude lakes) using observed LSWTs (ARC-Lake), for the period 1991 to 2010. This process substantially improves the measured mean differences in various features of the lake annual cycle, using only 3 lake properties (depth, snow and ice albedo and light extinction coefficient), as summarised in Table 5."

Replaces

"The 1-dimensional freshwater lake model, FLake, was successfully tuned for 244 globally distributed large lakes using observed LSWTs (ARC-Lake), for the period 1991 to 2010. This process substantially improves the measured biases in various features of the lake annual cycle (including saline and high altitude lakes), as summarised in Table 5 using only 3 lake properties (depth, snow and ice albedo and light extinction co-efficient)."

P8572 - line 24

"temperature, with a ~1:1 relationship shown (Fig. 17)."

Replaces

"temperature (1:1), Fig. 17."

P8572 - line 24-25

"This is highly useful where the lake-bottom temperature can not be or aren't observed directly."

Replaces

"This is highly useful where lake bottom temperatures can not be or isn't observed directly."

P8573 – line 19

“place of the default value”
Replaces
“place default value”

P8573 – lines 23-26
“The tuned model is forced with ERA data over the available time span of LSWT observations (16–20 years) but has the potential to be forced with ERA data covering a longer time span (ERA data are available for a period of > 33 years; 1979–2012).”

Replaces

“The tuned model forced with ERA data over the available time span of LSWT observations (16–20 years), has the potential to be forced with the complete time span of available ERA data, available for a period of > 33 years; 1979–2012.”

P8583 – Table 6 caption
“Comparison of metric results for seasonally ice-covered lakes: 135 lakes using the original tuned setup (Table 2), 25 lakes tuned with the modified set-up, all lakes, and trial lakes. The spread of differences across lakes is defined as 2σ.”

Replaces

“Metric results for seasonally ice-covered lakes (135 lakes using the original tuned setup, Table 2 and 25 lakes tuned with the modified set-up), compared with the results for the trial lakes, showing the spread of differences across lakes, 2σ.”

P8586 – Table 9 caption
“The fraction (R2adj) of observed inter-annual variance detected in the model. Maximum and minimum LSWT is used for non-seasonally ice-covered lakes (intermax and intermin), while JAS LSWT is used for seasonally ice-covered lakes, (interjas). This table highlights that where the observed inter-annual variance is low, the proportion of variance detected in the model is also low (high altitude seasonally ice-covered lakes and tropical lakes).”

Replaces

“The fraction (R2adj) of observed inter-annual variance detected in the model, for the maximum and minimum LSWT for non-seasonally ice covered lakes (intermax and intermin) and for the JAS LSWT for seasonally ice covered lakes, (interjas), highlighting that where the observed inter-annual variance is low, the proportion of variance detected in the model is also low (high altitude seasonally ice covered lakes and tropical lakes).”

P8605- Figure 16
The blue box with on top left hand side of figure reads “high snow and ice albedo”

Replaces

“high albedo”

P8577, Line 3
Layden, A., Merchant, C.J. and MacCallum, S.N.
replaces
Layden, A., Merchant, C. and MacCallum, S.

P8577,
A. Layden1, S.N. MacCallum2 and C.J. Merchant3
replaces
A. Layden1, S. MacCallum2 and C. Merchant

Comment from Referee 2

The authors gratefully acknowledge the time and attention given by the referees to their reviews, and the constructive comments made, to which we have paid close attention.

Referee Comments

I have one comment. On p. 8553-8554 (2.2.2 Fixed model parameters), authors listed parameters that remain fixed through the study and stated that water-to-ice heat flux (Q_wi) of 5 W/m-2 is applied to all lakes. To my knowledge, it's a strong overestimation. Malm et al. (Temperature and salt content regimes in three shallow ice-covered lakes: 2. Heat and mass fuxes. 1997. Nordic Hydrol., 28, 129-152) have shown temporal-spatial dynamics of Q_wi in shallow lakes. As it comes from their results, which can be considered as typical for shallow boreal lakes, Q_wi values for the main winter course - the ice thickness grows until early-spring radiative warming starts - are on average less than 1 W/m-2. During the 'warming' period, when ice starts melting, Q_wi may grow up to 10-15 W/m-2 due to rise of water temperature in the gradient layer beneath the ice. Concerning deeper lakes (D > 15-20 m), they usually get ice-covered much later that shallow ones. As a result, a greater loss of heat leads to water temperature in the upper part of a water column close to zero. Thus, Q_wi in deep lakes is close to zero as well. In *FLake*, ice 'grows' mainly from below unless a snow cover is present, and Q_wi is one of the main parameters in the process. I dare assume that ice thickness in calculations performed was erroneous. This, in its turn, demanded a kind of extra-tuning to adjust ice-off dates to realistic values.

All the tuning described inevitably produces unrealistic results on the water temperature vertical profile and depth of the mixed layer.

Then, my questions are:

1) **what is a main objective of the study?**
2) **who are expected to be end-users of a tuned model?**

Author's response – General

We acknowledge that the referee is concerned that a value of 5 W/m^{-2} applied to describe water-to-ice heat flux (icewater_flux) for the tuning of all lakes in *FLake,* may lead to erroneous ice thickness measurements. Furthermore, we acknowledge that icewater_flux can vary considerably between the ice growth and ice melt period. We have addressed these concerns through explanations and comments made.

Author response - Background on selection of icewater_flux values of 5 W/m^{-2}:

The icewater_flux value was selected during the preliminary modelling work in this study. The focus of the preliminary work was to find the lake properties which had the strongest effect on the modelled LSWTs. Seven (7) seasonally ice-covered lakes (deep and shallow), with available lake characteristic data in the ILEC world lake database (http://wldb.ilec.or.jp/) or LAKENET (www.worldlakes.org), were used in this preliminary work. For these lakes, icewater_flux values of 3 W/m^{-2} and 5 W/m^{-2} showed a negligible difference between the modelled daily mean absolute difference (MAD) LSWT values. On this basis a value 5 W/m^{-2} was used in the tuning study. Arguably, a value of 3 W/m^{-2} or 4 W/m^{-2} could have been applied.

Author response - Comment on extra-tuning to adjust ice-off dates to realistic values:

Agreed, it is very reasonable to suggest that extra-tuning is taking place in this approach, not only for the icewater_flux values but also for other factors, such as not using the modules, 'heat flux from sediments module' and the 'snow cover module'. The heat flux from the sediments module is not switched on in the tuning study, as outlined in P.8554, line 3. This is the suggested reason why shallow lakes are tuned to a greater depth i.e., extra tuning to greater depth to compensate for not considered heat flux from sediments (P.8570, line 14). Similarly, it is suggested that the 1 ^{o}C warming day occurs earlier (compared to observed LSWTs) because the snow cover module is not in use. The last paragraph in section 5.2 'Findings and Discussion', is now reworded to discuss the possibility of extra-tuning of albedo in this study.

Author response - Comment on unrealistic results on the water temperature vertical profile and depth of the mixed layer:

Yes, agreed. The tuning approach taken is specific to LSWTs. The metrics used in the tuning were chosen to capture the critical aspects of the LSWT cycle. For seasonally ice-covered lakes these are the maximum LSWTs (JAS), metrics indicative of ice-on/ ice-off and the MAD throughout the cycle. For non-ice-covered lakes, the difference between the observations and model for the months where the minimum (and maximum) LSWTs occur are applied as metrics. These exert some control over temporally reconciling the modelled monthly extremes with the observed monthly extremes.

The effect of the tuning on the temperature vertical profile and the depth of the mixed layer has not been considered in this study. Furthermore, the tuning of depth, particularly for lakes where depth is tuned to several times its depth, will most probably affect the temperature vertical profile and the mixed layer depth. I have now stated this in section 1 (Introduction) and explained that over-tuning is likely due to the few lake properties that are been considered in this study.

Author's Changes
Changes made to paper:

P8549, line 19 (Section 1: Introduction)

“*FLake* is a 1-dimensional thermodynamic lake model, capable of predicting the vertical temperature structure and mixing conditions of a lake (Mironov et al, 2010). The tuned model is expected to improve the representation of these lakes in *FLake*.

Replaces

“The tuned model is expected to improve the representation of these lakes in *FLake*.”

P8550, line 3 (Section 1: Introduction)

“It is the intention of this tuning study to achieve an average daily mean absolute difference (MAD) of ≤ 1 °C between the modelled (tuned) and observed LSWTs, across all lakes. A mean daily MAD of ≤ 1 °C is possibly accurate enough for a global scale study. A lower MAD target may not be achievable as this study comprises of lakes with a wide range of geographical and physical characteristics. The effect of the tuning on the sub-surface temperature profile and on the depth of the mixed layer is not considered in this study. Many lake-specific properties can be considered in *FLake.* Preliminary model trial work was carried out on 7 seasonally ice-covered lakes (deep and shallow) which had available lake characteristic data in the ILEC world lake database (http://wldb.ilec.or.jp/) or LakeNet (www.worldlakes.org). Through this preliminary work, the lake-specific properties which exerted the strongest effect on the modelled LSWTs were selected. These properties are lake depth (*d*), snow and ice albedo (α) and light extinction coefficient (κ). In the next part of the preliminary work, it was determined that the modelled LSWTs could be tuned to compare well with the observed LSWTs, by adjusting the values for these three properties: lake depth (*d*), snow and ice albedo (α) and light extinction coefficient (κ), herein referred to LSWT-regulating properties. On the basis of the preliminary findings, the trial work was performed on 35 lakes, prior to attempting to tune all 246 lakes.”

Replaces

“It is the intention of this tuning study to achieve an average daily mean absolute difference (MAD) of ≤ 1 °C, across all lakes. An average MAD of ≤ 1 °C is possibly accurate enough for a global scale study mean. A lower MAD target may not be achievable as this study comprises of lakes with a wide range of geographical and physical characteristics.

Many lake specific properties can be considered in *FLake.* Through preliminary model trials, three properties; lake depth **(*d*)**, albedo; snow and ice **($\boldsymbol{\alpha}$)** and light extinction coefficient **($\boldsymbol{\kappa}$)** are shown to greatly influence the modelled LSWT cycle. Furthermore, optimal values for these three properties (herein referred to LSWT regulating properties) are shown to greatly improve the LSWT modelling in *FLake*.”

New paragraph included at end of Introduction (section 1)

“Using the observed LSWTs (ARC-Lake), the objective of this study is to assess if *FLake* can be tuned to produce realistic LSWTs for large lakes globally, using relatively few lake properties. It is expected that for each lake, the tuning of lake properties will compensate to a greater or lesser degree for some of the lake to lake variability in geographical and physical characteristics. The motivation for this study was to develop a greater understanding of lake dynamics globally, offering the potential to help develop parameterization schemes for lakes in numerical weather prediction models. It is expected that the findings in this study will be of interest to climate modellers, limnologists and current and perspective users of *FLake*.

P.8568, last paragraph (section 5.1):

“There is a snow cover module with *FLake* which is not operational in this version of the model; therefore the insulating effect that snow has on the underlying ice is not modelled. As a result the snow and ice albedo are set to the same default value (0.60), possibly underestimating the extent of the albedo effect of snow. This may be the reason for the earlier 1 °C warming day and the higher JAS LSWTs, when modelled with the default albedo. As shown in the tuning process, a higher albedo results in a later 1 °C warming day (reducing the mean difference between the modelled and observed LSWTs) and as a result, reduces the period of time of the surface absorption of short-wave radiation, improving the mean JAS LSWTs. It is possible that the icewater_flux value of 5 W/m^{-2} may be an overestimation of the water-to-ice heat flux in the ice growth phase of deep and shallow lakes. This greater heat flux, leading to underestimated ice thickness, could have contributed to the large 1 °C warming day mean difference shown in table 5 (column 1). In a study by Malm et al. (1997), the water-to-ice heat flux during the ice growth phase was shown to be < 1 W/m^{-2} in both deep (15-20 m) and shallow lakes. Underestimated ice thickness, causing an early ice melt, may possibly have led to over-tuning of albedo in the tuned model.”

Replaces

“There is a snow cover module with *FLake* which is not operational in this version of the model, therefore the insulating effect that snow has on the underlying ice is not modelled. As a result the snow and ice albedo are set to the same default value (0.60), possibly underestimating the extent of the albedo effect of snow. This may be the reason for the earlier 1 ^oC warming day and the higher JAS LSWTs, when modelled with the default albedo. As shown in the tuning process, a higher albedo results in a later (and more timely) 1 ^oC warming day and as a result, reduces period of time of the surface absorption of short-wave radiation, improving the mean JAS LSWTs. “

Included at end of Summary and conclusion (section 6)

“The findings in this study are expected to be of interest to limnologists concerned with the relationship between certain features of the LSWT cycle and lake characteristics. Limnologists may also benefit from other aspects of this study, for example, the effect of wind speed scaling on LSWTs and how the observed minimum monthly LSWTs may be used to estimate lake-bottom temperatures. The optimal LSWT-regulating properties of the 244 lakes may provide a guide to current and prospective users of *FLake* for improving the LSWT modelling in *FLake* for other lakes, without having to tune the model for each lake separately. This is of particular use for lakes where lake characteristic information is not available. The described approach to this study can provide practical guidance to scientists wishing to tune *FLake* to produce reliable LSWTs for new lakes.

’Mironow’ corrected to ’Mironov’ throughout

Additional References

Malm, J., Terzhevik, A., Bengtsson, L., Boyarinov, P., Glinsky, A., Palshin, N. and Petrov M.: Temperature and salt content regimes in three shallow ice-covered lakes: 2. Heat and mass fluxes, Nordic Hydrol., 28, 129-152, 1997

Mironov, D., Heise, E., Kourzeneva, E., Ritter, B., Schneider, N. and Terzhevik, A.: Implementation of the lake parameterisation scheme FLake into the numerical weather prediction model COSMO. Boreal Env. Res., 15, 218-230, 2010

Comment from Referee 3

Anonymous Referee #3
Received and published: 9 December 2015

The authors gratefully acknowledge the time and care given by the referees to their reviews, and the constructive comments made, to which we have paid close attention.

This paper is a useful investigation into the adjustment of tuning parameters available with the FLake model. The authors demonstrate that the LSWT produced by the FLake model matches observations more closely using their improvements. This has been demonstrated for a large number of lakes, and has applications for extension to modelling of further lakes. This is therefore a very useful study to improve the accuracy of the FLake model for users.
Below I have provided comments in four sections: general comments, more specific comments, figures and tables, and technical corrections.

General comments

Referee comment
1. Needs an introductory paragraph outlining the application of this work, e.g. use of FLake in NWP etc; why is this work important.

Author's response
New paragraph included at end of Introduction (section 1)

Author's change

"Using the observed LSWTs (ARC-Lake), the objective of this study is to assess if *FLake* can be tuned to produce realistic LSWTs for large lakes globally, using relatively few lake properties. It is expected that for each lake, the tuning of lake properties will compensate to a greater or lesser degree for some of the lake to lake variability in geographical and physical characteristics. The motivation for this study was to develop a greater understanding of lake dynamics globally, offering the potential to help develop parameterization schemes for lakes in numerical weather prediction models. It is expected that the findings in this study will be of interest to climate modellers, limnologists and current and perspective users of *FLake*."

Referee comment
2. Throughout, rename "non-seasonally ice covered lakes" just "non-ice covered lakes" - much less confusing!

Author's response
Changed throughout

Referee comment
3. Table and figure captions should stand alone from text - the reader should not have to look up acronyms and definitions to understand them. Define all subscripts, acronyms and symbols as much as possible.

Author's response
All acronyms, symbols and terms are now explained in the table and figure cations

Referee comment
4. p 8552, line 1: By using an average of the day and night lake temperatures to get your LSWT observation, won't you get a sort of part diurnal signal? Would it not be

better to just use either nighttime (no diurnal signal) or daytime (diurnal signal)?

Author's response

Possibly yes. I don't expect that the model tuning would be greatly influenced by a diurnal signal in the observed LSWTs. The fact that it is a global scale study, it was considered best to fully utilise the data, as the average temporal resolution of LSWT retrievals is < 1 week. Using either day or night data, particularly in cloudy regions, could compromise retrievals.

Referee comment

5. "Biases" should really be "mean differences" throughout, as your reference dataset is not necessarily truth.

Author's response

Mean difference(s) is now used in place of bias throughout in text, tables,figures and captions.

Referee comment

6. Think about order of sections, and do not keep revisiting same topic if it can be put into one section, e.g. wind speeds.

Author's response

The application of wind speed scaling has been discussed in section 2.3.5 only and removed from section 2.2.3. Section 3 'Applied wind speeds' is now renamed as 'Trial results for wind speed scaling'

Specific comments

Referee comment

Abstract: clarify that the tuning is for individual lakes, not one tuning applied to 244 lakes. When mentioning differences (e.g. MAD), need to state differences to what reference.

Author's change A

"A tuning method for *FLake*, a 1-dimensional freshwater lake model, is applied for the individual tuning of 244 globally distributed large lakes using lake surface water temperatures (LSWTs) derived from Along-Track Scanning Radiometers (ATSRs)."

Replaces

"FLake, a 1-dimensional freshwater lake model, is tuned for 244 globally distributed large lakes using lake surface water temperatures (LSWTs) derived from Along-Track Scanning Radiometers (ATSRs)."

Author's change B

"The model, which was tuned using only 3 lake properties (lake depth, snow and ice albedo and light extinction co-efficient), substantially improves the measured mean differences in various features of the LSWT annual cycle, including the LSWTs of saline and high altitude lakes, when compared to the observed LSWTs."

Replaces

"The model, which was tuned using only 3 lake properties (lake depth, snow and ice albedo and light extinction co-efficient), substantially improves the measured mean differences in various features of the LSWT annual cycle, including the LSWTs of saline and high altitude lakes."

Author's change C

"For trial seasonally ice-covered lakes (21 lakes), the daily mean and standard deviation (2σ) of absolute differences (MAD) between the modelled and observed LSWTs, are reduced from 3.07 ± 2.25 °C to 0.84 ± 0.51 °C by tuning the model."

Replaces

"For seasonally ice-covered lakes, the daily mean and standard deviation (2σ) of absolute differences (MAD) are reduced by model tuning from 3.07 ± 2.25 °C to 0.84 ± 0.51 °C."

Referee comment

Introduction:

p. 8549, line 10: mention Great Lakes too, as these also have a significant effect on the local climate inducing lake-effect snow storms etc.

Author's changes

"The Great Lakes and the large Canadian lakes of Great Bear and Great Slave can alter the local climate through lake-effect storms, impacting on the fluxes of heat, moisture, and momentum, and on the mesoscale weather processes (Sousounis and Fritsch, 1994; Long et al., 2007)."

Replaces

"The large Canadian lakes of Great Bear and Great Slave can alter the local climate through lake-effect storms, impacting on the fluxes of heat, moisture, and momentum, and on the mesoscale weather processes (Long et al., 2007)."

References included:

“Sousounis, P.J., and Fritsch, J.M.: Lake-aggregate mesoscale disturbances. Part II: A case study on the effects on regional and synoptic-scale weather systems, Bull. Amer. Meteor. Soc., 75,1793-1811, 1994.”

Referee comment

p. 8550, line 2: difference to ...what? reference data - ARC-Lake observations

Author’s change

“It is the intention of this tuning study to achieve an average daily mean absolute difference (MAD) of $\leq 1\,^{\circ}$C between the tuned and observed LSWTs, across all lakes.”

Replaces

“It is the intention of this tuning study to achieve an average daily mean absolute difference (MAD) of $\leq 1\,^{\circ}$C, across all lakes.”

Referee comment

p. 8550, line 10: Give location of lake (country, or lat/lon)

Author’s change

“An example of the preliminary trial work is shown for Lake Athabasca (Canada), in Fig. 1a.”

Replaces

“An example of the preliminary trial work is shown for Lake Athabasca, in Fig. 1a.”

Figure 1 caption **“**Preliminary modelled runs for Lake Athabasca, Canada,…….”

Replaces

Figure 1 caption **“**Preliminary modelled runs for Lake Athabasca, …………”

Referee comment

p. 8550, line 14: It’s confusing here why you would want to use a shallower depth than the mean as this is less realistic. This is explained later on in the paper, but perhaps you should refer to this discussion or add an extra sentence to justify this a bit better.

Author’s change

“In Fig. 1b, it is demonstrated that by using a shallower *d* than the mean depth of the lake, the ice-on day occurs earlier and corresponds more closely to the observed ice-on day. Lake depth is essentially being used as a means to adjust the heat capacity of the lake, exerting control over the lake cooling and therefore the ice-on date.”

Replaces

“In Fig. 1b, it is demonstrated that by using a lower *d* than the mean depth of the lake, the ice-on day occurs earlier and corresponds more closely to the observed ice-on day.”

Referee comment

p. 8550: line 21: where do your observed LSWTs come from? (or put this section after you have introduced ARC-Lake)

Author’s response

ARC-Lake is introduced on the previous page (p. 8449: line 16) but have now included ARC-Lake to remind reader of the source.

Author’s change

“In this study, for each lake, the modelled mean differences for several features in the LSWT annual cycle are measured, quantifying the level of agreement with the observed LSWTs ARC-Lake LSWTs.”

replaces

“In this study, for each lake, the modelled mean differences for several features in the LSWT annual cycle are measured, quantifying the level of agreement with observed LSWTs.”

Referee comment

p. 8552: line 25: replace sentence beginning "Values for other lake" with "Other lake-specific properties adjusted for this study are:"

Author’s change

“Other lake-specific properties adjusted for this study are: c_relax_C, fetch, latitude and the starting conditions.”

Replaces

“Values for other lake-specific properties outlined in this section are retained throughout the investigative and tuning process.”

Referee comment

p. 8553: line 17: what is the spin-up time for the model?

Author’s response

Its very short, if the starting conditions are well estimated; a day or two for most lakes. The average spin up time included below (< 3 days)

Author’s change

"Starting conditions: these provide *FLake* with the lake specific initial temperature and mixing conditions: temperature of upper mixed layer, bottom temperature, mixed layer depth, ice thickness and temperature at air–ice interface. A good estimation of the starting conditions for each lake was obtained from the *FLake* model based on the hydrological year 2005/06 (Kirillin et al., 2011). Other than shortening the model spin-up time (to an average of <3 days), the starting conditions showed no influence over the modelled LSWTs thereafter."

Replaces

"Starting conditions: these provide *FLake* with the lake specific initial temperature and mixing conditions. Other than shortening the model spin-up time, the starting conditions showed no influence over the modelled LSWTs thereafter. The starting conditions are temperature of upper mixed layer, bottom temperature, mixed layer depth, ice thickness and temperature at air–ice interface. A good estimation of the starting conditions for each lake was obtained from the *FLake* model based on the hydrological year 2005/06 (Kirillin et al., 2011)."

Referee comment

p. 8553: line 26: The light extinction coefficient is one of the tuned properties, so this is very confusing. Do you mean in seasons other than summer? See also p. 8554, lines 4-6. Needs rewording.

Author's response

Yes, this is confusing. Light ext. coefficient is tuned but it remains fixed throughout the annual cycle of each lake. There is an option to include a variation but I've not used this. Instead I've tuned it at the most responsive part of the annual cycle i.e., summertime. I've removed all reference to variation in the light ext. coefficient (p. 8553: line 26 to p. 8554, lines 6 & p.8558, sect 2.4.1) . Instead I have pointed out (figure 6) the stronger effect of light ext. coefficient on the maximum LSWT than on the minimum LSWT.

Author's change A- p. 8553: line 26 to p. 8554

"The model parameters that remain fixed throughout the investigative and tuning process, across all lakes (fixed model parameters) are icewater_flux, inflow from the catchment and heat flux from sediments For icewater_flux, (heat flow from water to ice) G. Kirillin (personal communication, 2010) suggests values of ~ 3–5Wm^{-2}. In this study a value of 5Wm^{-2} is applied to all lakes. Inflow from the catchment and heat flux from sediments are not considered in this study. "

Replaces

"The model parameters that remain fixed throughout the investigative and tuning process, across all lakes (fixed model parameters) are icewater_flux, inflow from the catchment, heat flux from sediments and variation in the light extinction coefficient. For icewater_flux, (heat flow from water to ice) G. Kirillin (personal communication, 2010) suggests values of ~ 3–5Wm^{-2}. In this study a value of 5Wm^{-2} is applied to all lakes. Inflow from the catchment and heat flux from sediments are not considered in this study. The light extinction coefficient is only considered when its effect on LSWT is most prominent (summer time), as discussed in Sect. 2.4 (i.e., variations in the light extinction coefficient throughout the annual cycle are not considered)."

Author's change B - p. 8558, section 2.4.1
"The metrics and the effect of the LSWT-regulating properties on them, for seasonally ice-covered lakes is summarised in Table 3. The effect of light extinction coefficient on the JAS LSWTs is demonstrated in Fig. 7, showing that the tuned light extinction coefficient (κ_d) value, κ_{d6} in place of a lower (more transparent) κ_d value (κ_{d2}), described in Table 2, substantially improves the JAS LSWT, when compared to the observed LSWT. In this figure, the greater effect of light extinction coefficient on the maximum LSWT than on the minimum LSWT is also demonstrated."

Replaces

"The metrics and the effect of the LSWT regulating properties on them, for seasonally ice-covered lakes is summarised in Table 3. The light extinction co-efficient effect on the summertime LSWT; July, August and September (JAS) LSWT is demonstrated in Fig. 6, showing that the tuned κ_d value (κ_{d6}) substantially improves the JAS LSWT."

Referee comment
p. 8554, line 2: missing "-" in both units

Author's response
Corrected

Referee comment
p. 8554, section 2.3.3 - Suggest combining this section with others on wind speed.

Author's response
The application of wind speed scaling has been discussed in section 2.3.5 only and removed from section 2.2.3. Section 3 'Applied wind speeds' is now renamed as 'Trial results for wind speed scaling'

Referee comment
p. 8555, line 25: If this is a universal relation, then why change it between 2-10 m? Perhaps reword as the best thing to use if no other information is available.

Author's change

“Of the 5 studies, this formula produces the lowest (most transparent) κ values, potentially more representative of open water conditions of large lakes, and is therefore used in this study for lakes with Secchi disk depths of 2-10 m. In the absence of a light extinction coefficient formula outside this Secchi disk depth range (less than 2 m and greater than 10 m) that is suitable for large lakes, the Poole and Atkins (1929) formula is applied. This formula, Eq. (3), provides sufficiently accurate estimations of light extinction coefficients in waters with all degrees of turbidity (Sherwood, 1974).”

Replaces

“Of the 5 studies, this formula produces the lowest (most transparent) κ values, potentially more representative of open water conditions of large lakes, and is therefore used in this study. For Secchi disk depths outside the 2–10m range (less than 2m and greater than 10 m) the Poole and Atkins (1929) formula is applied. This formula, Eq. (3), is used as it is considered to serve as a universal relation between light extinction coefficient and Secchi disk depth data and provides sufficiently accurate estimations of light extinction coefficients in waters with all degrees of turbidity (Sherwood, 1974).”

Referee comment

p. 8556, line 11: What are the figures in brackets? This sentence is unclear.

Author’s change

“The spectra for these 10 ocean water types are divided (in fractions of 0.18, 0.54, 0.28) into three wavelengths: 375, 475 and 700nm, respectively.”

Replaces

“The spectra for these 10 ocean types are divided (0.18, 0.54, 0.28) into three wavelengths: 375, 475 and 700nm, respectively.”

Referee comment

p. 8557, section 2.3.4: Unclear here why 0.60 is too low, and not clear where this value came from.

Author’s response

This is now explained in more detail

Author’s change

“FLake uses two categories of albedo for snow (dry snow and melting snow) and two categories for ice (white ice and blue ice). As the snow cover module with *FLake* is not operational in this version of the model, the snow and ice albedo are set to the same default value in the *FLake* albedo module, 0.60 for dry snow and white ice and 0.10 for melting snow and blue ice. These default snow and ice albedo values are referred to as $\alpha 1$ in this study. During the preliminary trials, a higher albedo (than $\alpha 1$) was shown to delay ice-off,

substantially improving the timing of early ice-off, compared to observed LSWTs (demonstrated in Fig. 1a). A higher snow and ice albedo causes more of the incoming radiation to be reflected, resulting in a later ice-off. On this basis, we apply 3 additional albedos of higher values ($\alpha 2$: $\alpha 4$), shown in Table 2, for tuning seasonally ice-covered lakes. Albedo when discussed throughout this study refers to the albedo of snow and ice. The albedo of water (in liquid phase) is maintained at the default value of 0.07 throughout this study.

Replaces

"The model default albedo **(α)** value is 0.60 for snow and white ice and 0.10 for melting snow and blue ice, referred to as $\alpha 1$. On the basis of the modelled biases outlined in the introduction, we apply 3 additional albedos of higher values ($\alpha 2$: $\alpha 4$), shown in Table 2, when tuning of seasonally ice-covered lakes. A higher albedo causes more of the incoming radiation to be reflected, causing a later (and more timely) ice-off. Albedo when discussed throughout this study refers to snow and ice albedo."

Referee comment

p.8558, line 5: Need to define kappa here too.

Author's change

"…..showing that the tuned light extinction coefficient (κ_d) value, κ_{d6} (described in Table 2), substantially improves the JAS LSWT."

replaces

"…….showing that the tuned κ_d value (κ_{d6}) substantially improves the JAS LSWT."

Referee comment

p. 8559, equation 5: x mean is not defined. N is defined below the next equation, should be introduced here.

Author's change

$$var_{\mathrm{jas}} = \sum \left(x_i^{obs\_jas} - \bar{x} \right)^2 / (N - 1) \qquad (5)$$

where $^{obs\_jas}$ = observed mean JAS LSWT

$\bar{x}$ = mean across all years

N = number of years with JAS LSWTs

Replaces

$$var_{jas} = \sum (x_i^{obs\_jas} - \bar{x})^2 / (N - 1) \qquad (5)$$

Referee comment

p. 8559, section 2.4.4: Suggest putting this at start as introduction. Then can say each part is described in more detail below.

Author's response

Now referred to in the Introduction -Last line of 2nd last paragraph.

Figure captions and references from 2-8 are now renumbered

"An overview of the tuning approach applied to these two lake categories is shown in Fig. 2, and described in detail within section 2."

Removed from section 2.4.4

2.4.4 Overview of tuning method

"An overview of tuning approach for seasonally ice-covered lakes and non-ice covered lakes is shown in Fig. 8."

Referee comment

p. 8560, line 3: This still doesn't match particularly well, need to state this.

Author's response

This doesn't match well as the wind speed scalings are modelled using the untuned model. I've stated this now in the figure caption and have also referred to it in the text

Author's change

Figure 9 Effect of wind speed scalings on the modelled lake surface water temperature (LSWT) for Lake Simcoe, Canada (depth 25 m), showing that the greatest wind speed scaling, *u3* ($U_{water} = 1.62+1.17U_{land}$), in place of the unscaled wind speed, *u1,* reduces the daily mean absolute difference and July, August September LSWT mean difference by ~50%. Modelled with untuned LSWT- regulating properties: mean lake depth (Z_{d1}), default snow and ice albedo ($\alpha 1$) and light extinction coefficient derived from Secchi disk depth data (κ_{sd})

Replaces

Figure 9 Effect of wind speed scalings on the modelled lake surface water temperature (LSWT) for Lake Simcoe, Canada, showing that the greatest wind speed scaling, *u3* ($U_{water} = 1.62+1.17U_{land}$), in place of the unscaled wind speed, *u1,* reduces the daily mean absolute difference and July, August September LSWT mean difference by ~50%.

Author's change (**Section 3, Paragraph 1)**

“Wind speed was examined in the untuned model trial for both seasonally ice-covered lakes and non-ice covered lakes. Wind speeds, *u1, u2 and u3* were modelled with untuned LSWT properties: mean lake depth (Z_{d1}), default snow and ice albedo ($\alpha 1$) and light extinction coefficient derived from Secchi disk depth data (κ_{sd}). The trials show that wind speed has a consistent effect on the modelled LSWT of seasonally ice-covered lakes. The higher wind speed scaling (*u3*) causes earlier cooling and later warming (reducing the 1 °C cooling day and 1 °C warming day mean differences), lengthening the ice cover period and reducing the JAS LSWT, as demonstrated for Lake Simcoe, Canada in Fig. 9. It is expected that the tuning of *d, α* and *κ,* with an applied wind speed of *u3,* will produce modelled LSWTs substantially closer to the observed LSWTs than those shown in Fig. 6, where tuning of *d, α* and *κ* is not applied.”

Replaces

“Wind speed was examined in the untuned model trial for both seasonally and non-seasonally ice covered lakes. The trials show that wind speed has a consistent effect on the modelled LSWT of seasonally ice covered lakes. The higher wind speed scaling (*u3*) causes an earlier (and more timely) cooling and later (and more timely) warming, lengthening the ice cover period, as demonstrated for Lake Simcoe in Figure 9.”

Referee comment

p. 8560, line 9/10: Suggest replace half with 50%

Author’s response

done throughout

Referee comment

p. 8561, line 3: differences between modelled and observed

Author’s change

“The average MAD and spread of differences (2σ) between the modelled and observed LSWTs for seasonally ice-covered lakes and non-ice covered lakes,”

Replaces

“The average MAD and spread of differences (2σ) for seasonally ice-covered lakes and non-ice covered lakes,”

Referee comment

p. 8561, line 25: reword to make more of this. What did the 25 lakes have in common which makes them not fit? All shallow... anything else?

Author’s change

“Relative to the size (depth and area) of the larger seasonally ice-covered lakes, these 25 lakes are shallow (average mean depth < 5m) and small (18 of the 25 lakes are < 800 km^2). Twenty (20) of the 25 lakes are located in Eastern Europe or Asia, at relatively low altitudes; 22 of the 25 lakes are < 752 m a.s.l.. These 25 lakes were tuned to the highest depth factor, Z_{d4} (1.5 times the mean depth) and/or the highest light extinction coefficient, κ_{d5} (lowest transparency).”

Replaces

“These 25 shallow lakes (average depth < 5m) were tuned to the highest depth factor, Z_{d4} and/or the highest light extinction coefficient, κ_{d5} (lowest transparency).”

Referee comment

p. 8561, line 25: is Zd4 the highest depth factor? Use Zd5:Zd7 as greater depth factors later on... do you mean shallowest?

Author’s response

Yes Zd4 the highest depth factor (1.5 times mean depth) in the initial tuning of the 160 lakes. I expand the re-tuning the 25 shallow lakes to include 3 greater depth factors (2, 2.5 and 4 times the mean depth), renamed as Zd6:Zd8, as Zd5 was incorrectly referenced here (apologies for the confusion). This is now corrected in the text. I’ve also change the presentation of the corresponding table (table 2) – there is no bold text.

Author’s change A

Table 2 Effective depth factors (Z_d), light extinction coefficient values (κ_d) and snow and ice albedo values (α) used in tuning study. Eighty (80) possible combinations used for tuning of seasonally ice-covered lakes (Z_{d1} : Z_{d4} x κ_{d1} : κ_{d5} x $\alpha 1$: $\alpha 4$) . The modified tuning for the 25 shallow seasonally ice-covered lakes utilised greater depth factors; Z_{d6} : Z_{d8} and 2 higher light extinction coefficient values, κ_{d6} and κ_{d7}. Sixty (60) possible combinations used for tuning of non-ice covered lakes (Z_{d1} : Z_{d6} x κ_{d1} : κ_{d10}) . The spectre for the 10 κ_d values are divided (in fractions of 0.18, 0.54, 0.28) into three wavelengths: 375, 475 and 700nm, respectively.

Replaces

Table 2 Lake depth factors (Z_d), light extinction coefficient values (κ_d) and snow and ice albedo values (α) used in tuning study; 80 possible combinations for seasonally ice-covered lakes (plain text only) and 60 possible combinations for non-ice covered lakes (plain and bold text; all 6 Z_d factors x all 10 κ_d values)

Author’s change B - p.8562: line 8

“The tuning approach for these lakes is expanded to include 3 greater depth factors of 2.5, 2 and 4 times the mean depth ($Z_{d6,}$ Z_{d7} and Z_{d8}) and 2 higher light extinction coefficient values, κ_{d6} and κ_{d7} (Table 2).”

Replaces

“A tuning modification, using 3 greater depth factors, Z_{d5}: Z_{d7}, and 2 higher light extinction coefficient values, κ_{d6} and κ_{d7} (Table 2) is applied.”

Referee comment

p. 8562, line 9: Confused about the tuning modification - implies multiple depths and light extinction coefficients for each lake produce these results?

Author’s response

The tuning approach for the 25 shallow lakes was expanded to include greater depth factors and higher light extinction coefficients to allow. The changes made in relation to the previous comment addresses this comment.

Referee comment

p. 8563, line 10: Previous section suggests it is not successful - reconcile this.

Author’s change

“The results from the tuning approach applied to the 135 seasonally ice-covered lakes, the 84 non-ice covered lakes and the modified approach applied to the 25 shallow seasonally ice-covered lakes (described in Table 2) indicates that *FLake* is successful for tuning both saline and high altitude lakes, as well as freshwater and low altitude lakes. The tuned metrics categorized as saline, freshwater and low and high altitude lakes, are shown in Table 7 (seasonally ice-covered lakes) and in Table 8 (non-ice covered lakes).”

replaces

“The tuning of *FLake* is successful for both saline and high altitude lakes, as well as freshwater and low altitude lakes, as shown in Table 7 (seasonally ice-covered lakes) and in Table 8 (non-ice covered lakes).”

Referee comment

p. 8563, line 15: reference for this statement needed. Would have thought this effect was negligible.

Author’s response

Referee 1 has made similar comment. I have removed this statement and have now stated that altitude is considered through the altitude associated with meteorological data grid points.

Author’s change

“Although the density of freshwater in *FLake* is determined at sea level (normal atmospheric pressure) (Mironov, 2008) and the altitude of lakes are not directly considered in *FLake*, lake altitude (ranging from -12 to 5000 m a.s.l., over the 246 lakes) is considered indirectly through the geopotential height of the ERA forcing data."

replaces

"The density of freshwater in *FLake* is determined at sea level (normal atmospheric pressure) (Mironov, 2008). At higher altitudes, the lower water density results in less effective natural convective and thermal heat transfer processes. Although lake altitude is not considered in *FLake*, the effect of altitude (ranging from -12 to 5000 m a.s.l.,) on LSWT is shown to be minimal or else compensated for by the tuning process."

Referee comment

p. 8563, line 24/ p. 8564 line 4: variance of what?

Author's change

"The fraction (R^2_{adj}) of observed LSWT variance that is detected in the tuned model is quantified; $inter_{min}$ and $inter_{max}$ (non-ice covered lakes) quantifies the observed variance (K^2) in the month in which the minimum LSWT (var_{min}) and maximum LSWT (var_{max}) occurs and $inter_{jas}$ (ice-covered lakes) quantifies the observed variance (K^2) in the mean JAS LSWT (var_{jas})."

replaces

"The fraction of observed LSWT variance that is detected in the tuned model is quantified."

Referee comment

p. 8564, section 4.3.1: Give inter_min, inter_max definitions so reader does not have to look up.

Author's response

Now fully explained in preceding section (section 4.3) – see previous change

This section has been removed

"The fraction of observed LSWT variance (var_{min} and var_{max} for non-ice covered lakes and var_{jas} (K^2) for seasonally ice-covered lakes), that is detected in the tuned model ($inter_{min}$, $inter_{max}$, $inter_{jas}$ (R^2_{adj})), is determined as shown in Sect. 2.4.3."

Referee comment

p. 8565, line 6: only looking at 3 months so why is annual range relevant?

Author's response

Paragraph deleted

Referee comment

p. 8566, section 4.3.2: Why are results better for year with no tuning? Say something

about this. Interannual variability?

Author's change

"Although inter-annual variance may somewhat obscure year-on-year comparisons, the results of the modelled LSWTs for the untuned year (2011) compare well to the modelled results from the tuned years (1996 and 2010) showing that the model remains stable when run with ERA forcing data outside the tuning period."

replaces

"Overall, the result of the modelled LSWTs for the untuned year (2011) compare well to the modelled results from the tuned years (1996 and 2010) showing that the model remains stable when run with ERA forcing data outside the tuning period."

Referee comment

p. 8569, section 5.2: Explain the relationship between surface temperature and bottom temperature. What do the FLake profiles look like? Is there mixing, lack of diurnal heating etc?

Author's response

I've now explained the relationship between surface temperature and lake-bottom temperature. The lake-bottom temperatures were extracted during the stratification period, obtained from *FLake* model run using perpetual hydrological year, 2005/06. Other than all lakes showing a stratification period, the FLake profiles for these lakes were not examined.

Author's change

"Empirically, it has previously been shown that from the equator to approximately 40° (N/S), the steep decline in the minimum LSWT is reflected in the hypolimnion temperature (Lewis, 1996). This relationship is applicable to deep stratified non-ice covered lakes. For these lakes, the surface water, when at its coolest in the annual cycle (minimum LSWT) and therefore its densest, sinks to the lake-bottom. During the summer stratification period, the water in the upper mixed layer is warmer and less dense and therefore remains in the upper layer (with exception to high wind or storm conditions, which can induce intense vertical mixing). The strengthened density gradient in the summer thermocline (as demonstrated for Lake Malawi in Fig. 4) also protects the hypolimnion from heat flux through the lake surface. As a result, the lake hypolimnion temperature of deep non-seasonally ice covered lakes can reflect the minimum LSWT. The comparability between the monthly minimum LSWT (using the ARC-Lake monthly minimum climatology LSWTs) and the bottom temperature, for all deep (> 25 m) non-ice covered lakes (14 lakes) supports this empirical observation (Fig. 17)."

Replaces

"Empirically, it has previously been shown that from the equator to approximately 40° (N/S), the steep decline in the minimum LSWT is reflected in the hypolimnion temperature (Lewis, 1996). The comparability between the monthly minimum LSWT (using the ARC-Lake monthly minimum climatology LSWTs) and the bottom temperature, for all deep (> 25 m) non-ice covered lakes (14 lakes) supports this empirical observation.”

Referee comment

p. 8659, line 13: suggest "the maximum LSWT and the hypolimnion temperature" changed to "the two layers of the maximum LSWT and the hypolimnion temperature" if I have understood this correctly. The section is a little confusing.

Author’s response

I have reworded this below, referring to the lake surface (in the month of maximum LSWT) in the first instance.

Author’s change

“For the deep (> 25 m) non-ice covered lakes (14 lakes), the density difference between the lake surface (in the month of maximum LSWT) and the hypolimnion during the summer stratification period (when the density gradient of the thermocline is strongest, as illustrated in Fig. 4) was calculated (Haynes, 2013). The density gradient of the thermocline is dependent on the temperature difference between the lake surface and the hypolimnion. For lakes at latitudes below 35 °N/S, the average density difference between these two layers is substantially lower (0.352 x 10^{-3}kg/m^{-3}) than for lakes at latitudes above 35 °N/S (1.183 x 10^{-3}kg/m^{-3}). This is due to the smaller annual temperature range of the lower latitude lakes.”

Replaces

“For the deep (> 25 m) non-seasonally ice covered lakes (14 lakes), the density difference between the maximum LSWT and the hypolimnion temperature during the stratification period were calculated (Haynes, 2013). The density difference for lakes at latitudes below 35° N/S is substantially lower (0.352 x 10^{-3}kg/m^{-3}) than for lakes at latitudes above 35° N/S (1.183 x 10^{-3}kg/m^{-3}).
It is possible that the greater density difference between these two layers (LSWT and hypolimnion) in higher latitude lakes during the stratification period, may produce a stronger buffering effect against wind, than for lakes with a smaller density difference between the two layers.”

Referee comment

p. 8569, line 24: clarify density gradient is due to temperature difference.

Author’s response

Include in change for previous comment

Referee comment

p. 8570, line 1: "may show" - refer to later discussion

Author’s change

“As a result, higher latitude lakes may show more representative LSWTs using a higher wind speed scaling, as discussed in section 6.”

Replaces

“As a result, higher latitude lakes may show more representative LSWTs using a higher wind speed.”

Referee comment

p. 8570, line 7/p. 8573, line 15,16, Figure 18: change "lower" to "shallower" as lower depth means deeper. Similarly, "greater" depth should be "deeper" for consistency with this.

Author’s response Done

Referee comment

p. 8570, line 21: If there is no hypolimnion in FLake you need to reconcile this with section 5.2

Author’s change

Added to first paragraph in section 5.2

“Although *FLake* is a two-layer model; the depth of the hypolimnion layer is not calculated, the bottom modelled temperature is representative of the hypolimnion temperature, which remains constant with depth.”

Referee comment

p. 8570, section 5.4.1: So lake "depth" is not really depth but a tuning parameter influenced by depth. This could be described better.

Author’s response

The tuned lake depth is referred to as the effective depth. This is now clarified in **Section 2.3.3 –**

Author’s change **(in Section 2.3.3)**

“In the tuning process, depth factors (outlined in Table 2) are applied to the lake-mean depth. The tuned depth is referred to as the effective depth.”

Referee comment

p. 8571, line 5: give range as well as means so matches up with the <16 m, >16 m used below.

Authors response

The range of depths are wide for both kd values (1-138 m for kd5 and 1-57 m for kd4). I have reworded paragraph 1, reporting the average depth (16 m) and range of depths for all lakes (1-138). In paragraph 2, when applying kd4 /kd5 to the second model run I state that it makes sense to apply kd5 to shallower lakes, i.e., to lakes below the average depth (16 m).

Author's change

Section 5.4.2 – paragraph 1 and 2

"Across all lakes, 57% were tuned to light extinction coefficient values of κ_{d4} or κ_{d5}. These lakes are globally distributed and have a wide range of mean depths (1-138 m) with an average mean depth of 16 m. In view of this finding and considering that light extinction coefficient values are scarce for the majority of lakes, we assess if κ_{d4} and κ_{d5} can be used to provide a good estimation of the light extinction coefficient for modelling LSWTs in *FLake*.

The untuned model is forced using two sets of light extinction coefficient values and the MAD results are compared. In the first model run, the average κ_{sd} value (derived from Secchi disk depth data) of the trial lakes of each lake type is applied to all lakes of corresponding type. For the 21 seasonally ice-covered trial lakes, κ_{sd} = 0.82; for the 14 non-ice covered trial lakes, κ_{sd} = 1.46. In the second run, the model is forced with κ_{d4} or κ_{d5} values. κ_{d4} applied to all lakes > 16 m in depth (the average depth of lakes tuned with κ_{d4} or κ_{d5}) and κ_{d5} to all lakes < 16m in depth. It makes practical sense to apply the less transparent of these two κ_d values (κ_{d5}) to shallower lakes, as shallow lakes are generally more affected by lake bottom sediments than deeper lakes. For both model runs the default albedo and the mean depth are applied, while all other model parameters are kept the same."

replaces

"Across all lakes, 57% were tuned to light extinction coefficient values of either κ_{d5} and κ_{d5}. The average depth of lakes tuned to κ_{d4} is 21 m, and 13 m for lakes tuned to $\kappa_{d5.}$ Tuning of deeper lakes to the more transparent of these two κ_d value (κ_{d4}) and shallower lakes to the less transparent value (κ_{d5}) makes sense as water clarity of a shallower lake is more affected by the lake bottom sediments than that of deeper lake. In view of this finding and considering that light extinction coefficient values are scarce for the majority of lakes, we assess if κ_{d4} and κ_{d5} can be used to provide a good estimation of the light extinction coefficient for modelling LSWTs in *FLake*.

The untuned model is forced using two sets of light extinction coefficient values. All the seasonally ice covered lakes were modelled using the average κ_{sd} (0.82; derived from Secchi disk depth data) of the 21 trial lakes and the non-seasonally ice covered lakes were modelled using the average k_{sd} (1.46) of the 14 trial lakes. This is compared with the untuned model forced with κ_{d4} applied to lakes > 16 m in depth and with κ_{d5} for lakes < 16 m in depth. All other model parameters are kept the same. For both model runs the default albedo and the mean depth are applied."

Referee comment

p. 8572, section 5.4.3: You recommend alpha3 but have said you use alpha1, alpha2 and alpha3. Need to state something along lines of recommend alpha3 if no information is available.

Authors change

"For seasonally ice-covered lakes, only 19% of the lakes were tuned to the default snow and ice albedo, $\alpha 1$, (snow and white ice = 0.60 and melting snow and blue ice = 0.10). Sixty four (64) % of lakes were tuned to two higher albedos $\alpha 2$ or $\alpha 3$, (snow and white ice = 0.80 and melting snow and blue ice = 0.60 for $\alpha 2$ or 0.40 for $\alpha 3$), indicating that the default snow and ice albedo may be too low for the majority of lakes. In the absence of lake-specific snow and ice albedo information, the albedo value $\alpha 3$ (snow and white ice = 0.80, melting snow and blue ice = 0.40) may provide a good estimate. The $\alpha 3$ values are highly comparable to albedo values measured on a Lake in Minnesota using radiation sensors, where the mean albedo of new snow was shown to be 0.83 and the mean ice albedo (after snow melt) was 0.38 (Henneman and Stefan, 1999)."

Replaces

"For seasonally ice-covered lakes, only 19% of the lakes were tuned to the default snow and ice albedo, $\alpha 1$, (snow and white ice = 0.60 and melting snow and blue ice = 0.10). 64% of lakes were tuned to two higher albedos $\alpha 2$ or $\alpha 3$, (snow and white ice = 0.80 and melting snow and blue ice = 0.60 for $\alpha 2$ or 0.40 for $\alpha 3$), indicating that the default snow and ice albedo is too low. To reduce the mean differences in the ice-off and JAS LSWTs, the albedo value $\alpha 3$ (snow and white ice = 0.80, melting snow and blue ice = 0.40) is recommended in place default value ($\alpha 1$). The $\alpha 3$ values are highly comparable to albedo values measured on a Lake in Minnesota using radiation sensors, where the mean albedo of new snow was shown to be 0.83 and the mean ice albedo (after snow melt) was 0.38 (Henneman and Stefan, 1999)."

Referee comment

p. 8573, line 1: variance of what?

Authors change

"The amount of observed inter-annual LSWT variance (in the month in which the minimum LSWT and maximum LSWT occurs for non-ice covered lakes and in the JAS LSWT for ice covered lakes), detected in the tuned model was quantified. It can be concluded that lakes at lower latitude and high altitude (for all lakes where the observed LSWT variance is low and for non-ice covered where the annual range is low) are less well represented in the model, than lakes with greater observed LSWT variance and the annual range."

Replaces

“By determining the amount of observed LSWT variance detected in the tuned model, it can be concluded that lower latitude and high altitude lakes (lakes where the observed LSWT variance and annual range is low) are less well represented in the model, than lakes with greater observed LSWT variance and the annual range.”

Referee comment

p. 8573, line 9/10: add "between the *surface layer of* maximum LSWT" as it’s the density difference between two layers, rather than a temperature and a layer.

“A greater wind speed scaling for high latitude lakes may be required to overcome a greater buffering effect possibly caused by a greater temperature and density difference between the surface layer of maximum LSWT and the hypolimnion during stratification than in low latitude lakes.”

Replaces

“A greater wind speed scaling for high latitude lakes may be required to overcome a greater buffering effect possibly caused by a greater temperature and density difference between the maximum LSWT and the hypolimnion during stratification than in low latitude lakes.”

Referee comment

p. 8573, line 13: without having to tune the model? Surely the improvement is in how to tune the model for new lakes?

Author response

Tuning of FLake for new lakes would require applying a tuning process to the model that requires reliable observed LSWT information. This is now explained

Author change - p. 8573, line 11:

“The optimal LSWT regulating properties (effective depth, snow and ice albedo and light extinction) for the 244 lakes are shown to be sensible and may provide a guide to improving the LSWT modelling in *FLake* for other lakes, without having to apply a lengthy tuning process the model, requiring reliable observed LSWT information.”

replaces

“The optimal LSWT regulating properties of the 244 lakes are shown to be sensible and provide a guide to improving the LSWT modelling in *FLake* for other lakes, without having to tune the model.”

The closing paragraph includes

“The described approach to this study can provide practical guidance to scientists wishing to tune FLake to produce reliable LSWTs for new lakes.”

Referee comment

p. 8573, line 28: not "true changes" but rather long-term changes. Short term variability is still a true change.

Reference to true change removed

Author's change Now reads

"This offers the potential to provide a better representation of LSWTs changes over a longer period of time, as satellite observations for the relatively short period may reflect some inter-annual variance."

Referee comment

p. 8574, line 26: southern hemisphere rather than tropical.

Author's change Now reads

To overcome this problem, the lake bottom temperature for non-ice covered lakes in August; southern hemisphere winter, was used to set to the temperature of maximum density, before compiling and running the model.

Figures and Tables

Referee comment

Tables 4&5: "with the spread of differences" as you have used +- you are giving an uncertainty estimate so should describe it as such. Also need to specify that differences are between modelled and observed values.

Author's response

Captions updated – I have left the spread of difference as it is here, for the present, as I have referred to 'spread of differences' throughout text and tables. It also describes well, the spread of results across the number of lakes being examined. Did you intend for me to change to uncertainty estimates in table 4 and 5 only?

Author's change

"Table 4 The effect of wind speed scalings on untuned modelled LSWTs, presented as the mean difference, between the modelled and observed values, across lakes with the spread of differences defined as 2σ, where wind speeds *u1* is unscaled, *u2* is factored by 1.2 and *u3* (U_{water} = 1.62+1.17U_{land}). Results are presented for seasonally ice-covered and non-ice covered trial lakes. Results highlight that *u3* is most applicable to seasonally ice-covered lakes but there is no one wind speed most suited for all lakes (While the mean difference is improved with *u3*, the spread of the mean differences across lakes for mth_{min} and mth_{max} show little change)."

Replaces

The effect of wind speed scalings on untuned modelled LSWTs of the seasonally and non-seasonally ice covered trial lakes, with the spread of differences across lakes, 2σ. Results highlight that *u3* is most applicable to seasonally ice covered lakes but there is no one wind speed most suited for all lakes (While the average bias is improved with *u3*, the spread of biases across lakes for mth_{min} and mth_{max} show little change).

Referee comment

Table 5: Need to reword the caption.

Author's change Now reads

"Table 5 Summary of the untuned and tuned metrics for the trial lakes and the tuned metrics for all lakes (metrics are explained in Table 4). The results, presented for seasonally ice-covered and non-ice covered lakes in each instance, show the mean between the modelled and observed values, across lakes with the spread of differences defined as 2σ."

Replaces

"Summary of the untuned and tuned metrics for the trial seasonally and non-seasonally ice covered lakes and the tuned metrics for all seasonally and non-seasonally ice covered lakes showing the spread of differences across lakes, 2σ"

Referee comment

Table 10: Untuned has still been tuned with other parameters - need to say this

Author's change

"Table 10 Results of independent evaluation of the tuning process for seasonally ice-covered lakes. The spread of differences across lakes is defined as 2σ. These results illustrate that the metrics (explained in Table 4) from the untuned year (2011) compare well with metrics from 1996 (the first full year of data from Along-Track Scanning Radiometers 2 (ATSR2) and 2010 (the last year of tuned data from Advanced ATSR. For the untuned year (2011), for each lake, the model is forced with the effective lake depth (zd), snow and ice albedo (α) and light extinction coefficient (κd) values determined during the tuning process, shown in the supplement."

Replaces

Results of independent evaluation of the tuning process for seasonally ice covered lakes with the spread of differences across lakes, 2σ, showing that the metrics from the untuned year (2011) compare well with metrics from 1996 (the first full year of data from ATSR2) and 2010 (the last year of tuned data from AATSR)

Table 11 Results of the independent evaluation of the tuning process for non-ice covered lakes. The spread of differences across lakes is defined as 2σ. Metrics (explained in Table 4) for the untuned year (2011) are compared with those from the first full year of data from Along-Track Scanning Radiometers 2 (ATSR2) (1996) and the last year of tuned data from Advanced ATSR (2010). For the untuned year (2011), for each lake, the model is forced with the effective lake depth (z*d*), snow and ice albedo (*α*) and light extinction coefficient (*κd*) values determined during the tuning process, shown in the supplement.

Replaces

Table 11 Results of the independent evaluation of the tuning process for non-seasonally ice covered lakes 3 with the spread of differences across lakes, 2σ, showing the untuned year (2011) with the first full year of data from ATSR2 (1996) and the last year of tuned data from AATSR (2010)

Referee comment

Figure 1: Where do the observed values come from?

Reference to ARC-lake LSWTs included in the caption

Referee comment

Figure 2: State Lake Malawi is in southern hemisphere. Make clear the plots are FLake predictions. If you refer to the "upper mixed layer" and "bottom layer" in the caption these should be shown on plot.

Author reponse.

The figure is constructed from ILEC database information (now included in caption) – the aspects of the temperature and mixing profile that are capable of being predicted by FLake are highlighted in the caption. The caption is updated to reflect this more clearly

Author's change

"Figure 4 Summer and winter mixing and temperature profile of Lake Malawi, Africa (12° S 35° E), illustrated using data from the ILEC world lake database (http://wldb.ilec.or.jp/); showing the summer and winter lake water surface temperature (LSWT), mixed layer depth, thermocline temperature gradient and the hypolimnion. *FLake* is a two-layer model, capable of predicting the LSWT, the depth and temperature of the 'upper mixed layer' and the temperature of the 'bottom layer' "

Replaces

Figure 4 Summer and winter mixing and temperature profile of Lake Malawi; showing a mixed layer depth of 40-100 m. *FLake* predicts the LSWT and depth of the 'upper mixed layer' and the temperature of the 'bottom layer'

Referee comment

Figure 5: At 10 m there is a range of 50% of y-axis value, so not that close.

Have included the word 'reasonably', now reads (also included in Text)

"A comparison of 5 methods relating light extinction coefficients to Secchi disk depths, showing that all method compare reasonably well at Secchi disk depths > 10 m"

Referee comment

Figure 6: Would be good to see a similar plot with observed kappa too. Give country or lat/lon for Lake Geneva.

Now included - Lake Geneva, Europe (46º N 6º E), - I have done this for all lake-specific figure captions

Lake Geneva was not one of the trial lakes – so I haven't modelled it with light extinction derived from Secchi disk data.

For the trial lakes (untuned model), the average results and the spread of differences across the lakes are in table 5. For seasonally ice-covered trial lakes, the mean difference between the modelled and observed JAS LSWTs (3.71 $\pm$ 3.51 ^{o}C) indicate that the light ext. coeff used are not suitable. JAS LSWT mean difference is reduced to -0.12 $\pm$ 1.09 ^{o}C after tuning - keeping in mind that this the post-tuning result of depth, light ext and albedo.

Referee comment

Figure 7: Would like to see mean depth x 1.0 too

Author's response

I recall having this shown with mean depth at some stage but I removed it as it was it sat halfway between the depth x 0.5 and depth x 1.5 - it didn't add anything as such-just slightly cluttered the figure

Figure 8: Specify what "model forcing data:wind" equations are for (what categories of size). Need to clarify that e.g. 80 outputs per lake is to do with the various combinations

Author's response

Figure 8 is now Figure 2

Author's change

"Figure 2 Study approach overview (trials, tuning, evaluation and results) for a) seasonally ice-covered lakes and b) non-ice covered lakes. For the trials, wind speed scaling, *u1*, *u2* (recommended for lakes with fetch < 16 km and *u3* recommended for open ocean water) is assessed on the untuned model, tuning is then trialed with a range of factors for *d* and values for *α* and *κ* using the selected wind speed scaling*.* The tuning approach produces modelled LSWTs for all possible combination of *d*, *α* and *κ*, 80 modelled runs for seasonally ice-covered lakes and 60 for non-ice covered lakes. For the evaluation, the tuning metrics (normalized and equally weighted) are the basis for selection of the optimal (tuned) LSWT model for each lake."

Referee comment

Figures 9/10: need to refer back to u1, u3 etc in the text

Author's change

"Figure 9 Effect of wind speed scalings on the modelled lake surface water temperature (LSWT) for Lake Simcoe, Canada, 44° N 79° W (depth 25 m), showing that the greatest wind speed scaling, *u3* (U_{water} = 1.62+1.17U_{land}), in place of the unscaled wind speed, *u1,* reduces the daily mean absolute difference and July, August September LSWT mean difference by ~50%. Modelled with untuned LSWT properties: mean lake depth (Z_{d1}), default snow and ice albedo (*α1*) and light extinction coefficient derived from Secchi disk depth data (κ_{sd}) "

Replaces

Figure 9 Effect of wind speed scalings on modelled LSWT for Lake Simcoe, Canada, showing that the *u3* scaling halves the daily MAD and JAS LSWT bias

Author's change

"Figure 10 Effect of wind speed scaling on lake surface water temperatures (LSWT) for a temperate non-ice covered lake a) Lake Biwa, Japan (36° N 136 ° E) and for a tropical non-ice covered lake b) Lake Turkana, Africa (4° N 36 ° E) showing that the modelled LSWT for the temperate lake is better represented using *u3* (U_{water} = 1.*62*+1.17U_{land}), and the modelled LSWT for the tropical lake is better represented using *u1* (unscaled wind speed). mth_{min} (and mth_{max}) is the difference between the observed and modelled LSWTs for the month where the minimum (and maximum) LSWT is observed"

Replaces

"Figure 10 Effect of wind speed scaling on LSWT for a temperate non-seasonally ice covered lake a) Lake Biwa, Japan (35.6° N) and for a tropical non-seasonally ice covered lake b) Lake Turkana, Africa (3.5° N) showing that the modelled LSWT for the temperate lake is better represented using *u3* and the modelled LSWT for the tropical lake is better represented using *u1"*

Referee comment

Figure 11: "lakes tuned with modified are" doesn't make sense, reword

Author’s change

“Figure 11 Tuning metric mean differences between modelled and observed LSWTs for all 160 lakes with seasonal ice-cover. The results for the 25 lakes tuned with modified tuning approach are marked by diamond symbols a) July August September (JAS) LSWT mean difference, b) Daily mean absolute difference (MAD), c) 1 °C cooling day mean difference and d) 1 °C warming day mean difference”

Replaces

Figure 11 Tuning metric results for all 160 lakes with seasonal ice cover. The results for the 25 lakes tuned with modified are marked by diamond symbols a) JAS bias, b) MAD bias, c) 1 °C cooling day bias and d) 1 °C warming day bias

Referee comment

Figure 14: write out the default albedo for comparison

Author’s change

“Figure 14 Lake surface water temperatures (LSWTs) for Great Bear (66° N 121° W) and Great Slave (62° N 114° W)modelled with low snow and ice albedo (default albedo, $\alpha 1$: snow and white ice = 0.60 and melting snow and blue ice = 0.10) and high albedo ($\alpha 2$: snow and white ice = 0.80 and melting snow and blue ice = 0.60) demonstrating that the higher snow and ice albedo delays the 1 °C warming day, causing a lower July August September LSWT”

replaces

“Figure 14 LSWTs for Great Bear and Great Slave modelled with low albedo (default albedo) and high albedo (snow and white ice = 0.80 and melting snow and blue ice = 0.60) demonstrating that the higher albedo delays the 1 °C warming day, causing a lower JAS LSWT”

Referee comment

Figure 15: need to reword, as "C decrease per week of later 1C warming day" doesn’t make sense. More responsive than what? Also, this is only suggested by the plot, as the sample size is very small and therefore can’t be statistically significant. Need to be careful with your wording, both here and in the text.

Author’s response – presenting the results in JAS LSWT change per week of delayed warming is needed to be able to do a like for like comparison across lake – I tried to explain this a bit better.

Author’s change A **-** P 8567: line 4, reference to figure 15 is reword in text

“In Fig. 15, the lake-mean depth of the 21 trial lakes are plotted against latitude. The relationship between the depth and latitude of the lakes and the change in the JAS LSWT caused by the later 1 °C warming day (due to the higher albedo), is shown in this figure, by use of coloured circles. This figure shows that for deep high latitude lakes the decrease in the JAS LSWT (presented as the decrease in the JAS LSWT, per week of later 1 °C warming day, °C week^{-1}), is more pronounced than for shallow low latitude lakes."

Replaces

"The relationship between lake depth and latitude and the JAS LSWT decrease per week of later 1 °C warming day, shown in Figure 15, demonstrates the greater JAS LSWT change for deeper higher latitude lakes".

Author's change B **- Figure 15 caption**

"Figure 15 The relationship between latitude and lake-mean depth of the 21 trial ice-covered lakes and the decrease in the July August September (JAS) lake surface water temperature (LSWT) caused by the later 1 °C warming day (as a result of using a high albedo, *α2*: snow and white ice = 0.80 and melting snow and blue ice = 0.60 in place of the default albedo *α1*: snow and white ice = 0.60 and melting snow and blue ice = 0.10). The changes in the JAS LSWT, presented as the decrease in the JAS LSWT, per week of later 1 °C warming day, °C week^{-1}, are categorised by coloured circles. This figure indicates that high latitude and deep lakes show a larger decrease in the JAS LSWT per week of later 1 °C warming day, signifying that the LSWTs of these lakes are more responsive to changes in the 1 °C warming day, than low latitude and shallow lakes. "

Replaces

"The JAS LSWT decrease (shown as °C decrease per week of later 1 °C warming day) caused by a higher albedo for the 21 trial lakes shown with respect to lake depth and latitude. This figure shows that high latitude and deep lakes show largest JAS LSWT decrease with later 1 °C warming day, signifying that the LSWT of high latitude and deep lakes are more responsive to changes in the 1 °C warming day"

Referee comment

Figure 17: Stated in the text there's a 1:1 relationship but the equation you have supplied gives 1.02 (plus offset). I would suggest just not showing this equation. If lake is stratified, how do surface temperatures match bottom? What do FLake profiles look like? Is FLake forced with observed data here (non-independent)? What does this plot look like for other months?

Authors response

How surface temperatures can reflect bottom temperature is now included in the text in section 5.2. This version of *FLake* is an online version that models the perpetual hydrological year, 2005/06, The forcing for this model is independent; adopted from the Global Data Assimilation System (GDAS).

All lakes in the Flake profile showed a stratification period, other than that, the Flake profiles for these lakes were not examined. The lake bottom temperature during the stratification period was extracted from the modelled results

Authors change - **Cation**

“Figure 17 Comparison of lake-bottom temperatures during the stratification period, obtained from *FLake* model run using perpetual hydrological year, 2005/06 (Kirillin et al., 2011) and the monthly minimum climatology lake surface water temperature (LSWT) observations from ARC-Lake, for 14 deep (> 25 m) non-ice covered lakes (55 °S to 40 °N). The monthly minimum observed LSWTs have a ~1:1 relationship with the lake-bottom temperatures during the stratification period.”

Replaces

“Lake bottom temperature during stratification and climatological monthly minimum LSWT of 14 deep (>25 m) non-seasonally ice covered lakes from 55° S to 40° N, showing the modelled equilibrium result (lake bottom temperatures obtained from *Flake* lake model, using perpetual hydrological year, 2005/2006) compared with observed monthly minimum climatology LSWTs from ARC-Lake “

Technical corrections

p. 8550, line 4: global scale study mean does not make sense, reword

“An mean daily MAD of ≤ 1 °C is possibly accurate enough for a global scale study.”

p. 8550, line 16: remove comma

removed

p. 8550, line 17: "result" should be "results"

corrected

p. 8551, line 3: Last sentence of this paragraph needs rewording.

In order to capture the critical features of both ice-covered and non-ice covered lakes, the mean difference in the features between the observed and modelled LSWTs differ with lake type.

replaces

To capture the critical features in the LSWT cycle, the mean differences quantified, differ for the 2 lake categories

p. 8551, line 9: "includes" should be "including"
corrected

p. 8551, line 22: "demonstrates" should be "demonstrate"
corrected

p. 8552, line 19: remove comma after "Although"
corrected

p. 8552, line 23: remove semi-colon after "properties"
corrected

p. 8555, line 4: "coefficients" should be "coefficient"
corrected

p. 8555, line 15: "become" should be "becomes"
corrected
p. 8558, line 5: "tuning of seasonally" remove "of"
corrected
p. 8558, line 3: "is" should be "are"
corrected
p. 8558, line 9: erroneous bracket
corrected
p. 8559, line 16: should be "overview of *the* tuning"
corrected
p. 8561, line 7: remove the first "default"
corrected
p. 8562, line 16: "are" should be "is"
corrected
p. 8565, line 7: replace "possible" with "probably"
paragraph removed
p. 8566, line 13: add "timing *of the* 1C cooling day"
p. 8566, line 20: remove comma after "lakes"
corrected

p. 8567, line 23: remove "of"
corrected
p. 8567, line 24: "become" should be "becomes"
corrected

p. 8568, line 2: add "timing of *the* 1C warming"
corrected
p. 8568, line 12: replace comma after model with a semi-colon
corrected
p. 8568, line 17: add "reduces *the* period"
corrected
p. 8568, line 26: replace "being" with "been"
corrected
p. 8569, line 3: remove comma after although
corrected
p. 8569, line 4: replace "satellite" with "satellites"
corrected
p. 8571, line 5: replace "and" with "or"; need "m" after "21"
paragraph reworded

p. 8571, line 8: add "of *a* deeper"
paragraph reworded

p. 8571, line 10: replace "scare" with "scarce"
corrected

p. 8571, line 15: k used instead of kappa
corrected

p. 8571, line 20: remove comma after "runs" and replace "show" with "shows"
corrected

p. 8572, line 25: replace "isn’t" with "aren’t"
corrected

p. 8573, line 4: remove "the" from "the annual range"
corrected

p. 8573, line 16: remove comma after "18"
corrected

p. 8573, line 19: add "place *of the* default"
corrected
p. 8574, line 4: replace "quantity" with "quantify"
corrected

Submission to European Geosciences Union; Geoscientific Model Development (GMD)

Determining lake surface water temperatures (LSWTs) worldwide using a tuned 1-dimensional lake model (*FLake*, v1)

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Abstract

A tuning method for *FLake*, a 1-dimensional freshwater lake model, is ~~tuned~~applied for the individual tuning of 244 globally distributed large lakes using observed lake surface water temperatures (LSWTs) derived from Along-Track Scanning Radiometers (ATSRs). The model, which was tuned using only 3 lake properties~~;~~ (lake depth, snow and ice albedo and light extinction ~~co-efficient,~~coefficient), substantially improves the measured ~~biases~~ mean differences in various features of the LSWT annual cycle, including the LSWTs of saline and high altitude lakes~~. The~~, when compared to the observed LSWTs. Lakes whose lake-mean LSWT persists below 1 °C for part of the annual cycle are considered to be 'seasonally ice-covered'. For trial seasonally ice-covered lakes (21 lakes), the daily mean and standard deviation (2σ) of absolute differences (MAD) ~~and the spread of differences (± 2 standard deviations) across the trial seasonally ice covered lakes (lakes with a lake-mean LSWT remaining below 1 °C for part of the annual cycle) is~~ between the modelled and observed LSWTs, are reduced from 3.~~01 ±~~07 ± 2.25 ~~°C (pre-tuning)~~ °C to 0.84 ~~±~~± 0.51 ~~°C (post-~~ °C by tuning~~).~~ the model. For ~~nonseasonally ice-covered~~all other trial lakes (14 non-ice covered lakes ~~with a lake-mean LSWT remaining above 1 °C throughout its annual cycle), the average daily mean absolute difference (MAD) is reduced~~), the improvement is from 3.55 ± 3.20 ~~°C~~°C to 0.96 ± 0.63 ~~°C~~°C. The post tuning results for the 35 trial lakes ~~(35~~ (21 seasonally ice-covered lakes and 14 non-ice covered lakes) are highly representative of the post-tuning results of the 244 lakes.

The ~~sensitivity of~~relationship between the changes in the summer-LSWTs of deeper lakes ~~to~~and the changes in the timing of ice-off is demonstrated. The modelled summer-LSWT response to changes in ice-off timing is found to be statistically related to lake depth and latitude, which together explain 0.50 ($R^2_{adj,}$ p = 0.001) of the inter-lake variance in summer LSWTs. Lake depth alone explains 0.35 (p = 0.003) of the variance. ~~The tuning approach undertaken in this study, over~~Lake characteristic information (snow and ice albedo and

light extinction coefficient) is not available for many lakes. The approach taken to tune the model, bypasses the need to acquire detailed lake characteristic values. Furthermore, the tuned values for lake depth, snow and ice albedo and light extinction coefficient for the 244 lakes provide some guidance on improving *FLake* LSWT modelling.

~~comes the obstacle of the lack of available lake characteristic information snow and ice albedo and light extinction coefficient) for individual lakes. Furthermore, the tuned values for lake depth, snow and ice albedo and light extinction co-efficient for the 244 lakes provide guidance for improving LSWTs modelling in *FLake*.~~

1 Introduction

The response of LSWTs to climate is highly variable and is influenced by lake physical characteristics (Brown and Duguay, 2010). Some large lakes have been shown to alter the local climate. The extent of ice cover on lakes is considered to be a sensitive indicator of and also a factor in global change (Launiainen and Cheng, 1998). Changes in the length of the ice cover period affect local climatic feedbacks, for example, a shorter ice cover period allows ~~for~~ a longer time for surface heat exchange with the atmosphere (Ashton, 1986). This is of particular importance in areas where there is a high concentration of lakes, such as Canada (Pour et al., 2012). The Great Lakes and the large Canadian lakes of Great Bear and Great Slave can alter the local climate through lake-effect storms, impacting on the fluxes of heat, moisture, and momentum, and on the mesoscale weather processes (Sousounis and Fritsch, 1994; Long et al., 2007). Shallow lakes, particularly those with a large surface area, such as Lake Balaton, are more sensitive to atmospheric events (Voros et al., 2010).

~~such as Lake Balaton, are more sensitive to atmospheric events (Voros et al., 2010).~~

Reliable modelling of LSWTs can enrich our understanding of the highly variable dynamic nature of lakes. In this paper, a ~~1-dimensional~~ freshwater lake model, *FLake* (available at http://www.flake.igb-berlin.de/sourcecodes.shtml), is tuned with ATSR Reprocessing for Climate: Lake Surface Water Temperature and Ice Cover (ARC-Lake) observations (MacCallum and Merchant, 2012) of 244 globally distributed lakes. ~~The~~

FLake is a 1-dimensional thermodynamic lake model, capable of predicting the vertical temperature structure and mixing conditions of a lake (Mironov et al, 2010). The tuned model is expected to improve the representation of these lakes in *FLake*.

There have been some modelling studies carried out that use both the *FLake* model and LSWT observations on European lakes (Voros et al., 2010; Bernhardt et al., 2012; Pour et al., 2012). The findings of two of these three studies show consistent ~~biases~~

mean differences between the modelled and observed LSWTs (overestimation of the open water LSWTs and underestimation of the ice cover period). Despite these ~~biases~~mean differences, *FLake* is considered to be a reliable model for studying LSWTs and ice phenology and is considered suitable for global application for ice-covered lakes (Bernhardt et al., 2012). These modelled ~~biases~~mean differences (overestimation of the open water LSWTs and underestimation of the ice cover period) are consistent with findings from preliminary trial work carried out in this study, which included North American and European lakes.

It is the intention of this tuning study to achieve an average daily mean absolute difference (MAD) of $\leq$ 1 ~~ºC~~°C between the modelled (tuned) and observed LSWTs, across all lakes. ~~An average~~A mean daily MAD of $\leq$ 1 ~~ºC~~°C is possibly accurate enough for a global scale study~~ mean~~. A lower MAD target may not be achievable as this study comprises of lakes with a wide range of geographical and physical characteristics. The effect of the tuning on the sub-surface temperature profile and on the depth of the mixed layer is not considered in this study. Many lake-specific properties can be considered in *FLake*. Preliminary model trial work was carried out on 7 seasonally ice-covered lakes (deep and shallow) which had available lake characteristic data in the ILEC world lake database (http://wldb.ilec.or.jp/) or LakeNet (www.worldlakes.org). Through this preliminary work, the lake-specific properties which exerted the strongest effect on the modelled LSWTs were selected. These properties are lake depth (d), snow and ice albedo (α) and light extinction coefficient (κ). In the next part of the preliminary work, it was determined that the modelled LSWTs could be tuned to compare well with the observed LSWTs, by adjusting the values for these three properties: lake depth (d), snow and ice albedo (α) and light extinction coefficient (κ), herein referred to LSWT-regulating properties. On the basis of the preliminary findings, the trial work was performed on 35 lakes, prior to attempting to tune all 246 lakes.

~~Many lake specific properties can be considered in *FLake*. Through preliminary model trials, three properties; lake depth (d), snow and ice albedo (α) and light extinction coefficient (κ) are shown to greatly influence the modelled LSWT cycle. Furthermore,~~

~~optimal values for these three properties (herein referred to LSWT regulating properties) are shown to greatly improve the LSWT modelling in *FLake*.~~

An example of the preliminary trial work is shown for Lake Athabasca, Canada (mean depth of 26 m), in Fig. 1a. In this figure, a greater modelled *α* (higher reflectivity) results in a later ice-off date than the default model snow and ice albedo and is closely comparable to the observed ice-off date. In Fig. 1b, it is demonstrated that by using a ~~lower~~shallower *d* than the mean depth of the lake, the ice-on day occurs earlier and corresponds more closely to the observed ice-on day. ~~The~~

~~modelled LSWT~~Lake depth is essentially being used as a means to adjust the heat capacity of the lake, exerting control over the lake cooling and therefore the ice-on date. The modelled LSWT is further improved~~,~~ by lowering the *κ* value (greater transparency). The greater transmission of surface heat to the lower layers ~~result~~results in a lower and more

representative maximum LSWT, Fig. 1b. The LSWTs modelled using a combination of the greater *α*, lower *d* and lower *κ* compare closely with the observed LSWTs, Fig. 1c.

In this study, for each lake, the modelled ~~biases~~mean differences for several features in the LSWT annual cycle are measured, quantifying the level of agreement with the observed ARC-Lake LSWTs. These modelled ~~biases~~mean differences are the basis for selecting the tuned (optimal) LSWT-regulating properties (*d*, *α* and *κ*) for each lake. Lakes are divided into 2 distinct categories. Lakes with a lake-mean LSWT climatology (determined using twice-a-month ARC-Lake full year LSWT observations, 1992/1996–2011) remaining below 1 °C for part of the seasonal cycle are referred to as seasonally ice-covered lakes (160 lakes). All other lakes are referred to as non-~~seasonally~~ ice covered lakes (86 lakes). Although some of the seasonally ice-covered lakes may not be completely ice-covered during the cold season and some of the non-~~seasonally~~ ice covered lakes may have short periods of partial ice cover, the 1 °C lake-mean LSWT offers a good means of evaluating lakes that are typically and non-typically ice-covered during the coldest part of the LSWT cycle. ~~To~~In order to capture the critical features of both seasonally ice-covered and non-ice covered lakes, the mean difference in the ~~LSWT cycle, the biases quantified~~features between the observed and modelled LSWTs differ ~~for~~

~~the 2~~with lake type. An overview of the tuning approach applied to these two lake categories~~.~~ is shown in Fig. 2, and described in detail within Sect. 2.

Using the observed LSWTs (ARC-Lake), the objective of this study is to assess if *FLake* can be tuned to produce realistic LSWTs for large lakes globally, using relatively few lake properties. It is expected that for each lake, the tuning of lake properties will compensate to a greater or lesser degree for some of the lake to lake variability in geographical and physical characteristics. The motivation for this study was to develop a greater understanding of lake dynamics globally, offering the potential to help develop parameterization schemes for lakes in numerical weather prediction models. It is expected that the findings in this study will be of interest to climate modellers, limnologists and current and perspective users of *FLake*.

2 Methods

2.1 Data~~;~~: ARC-Lake observed LSWTs

~~The ARC-Lake~~ LSWT observations ~~for~~from ARC-Lake are used to tune the model. These cover 246 globally distributed large lakes, principally those with surface area > ~~500 km2~~2500km^2 (Herdendorf, 1982; Lehner and Döll, 2004) but ~~includes~~

also including 28 globally distributed smaller lakes, the smallest of which is 100 km^2 (Lake Vesijarvi~~) are used to tune the model. These~~). The LSWTs are generated from three Along-Track Scanning Radiometers (ATSRs), from 1991–2011 (MacCallum and Merchant, 2012). A synopsis of the derivation and validation of these observations is available in Layden et al. (2015).

The ARC-Lake observations have been shown to compare well with in situ LSWT data. Validation of the observations was performed through a match-up data set of in situ temperature data consisting of 52 observation locations covering 18 of the lakes (MacCallum and Merchant, 2012). Furthermore, the timing of ice-on and ice-off events is observed to be consistent with in situ measurements. This is demonstrated through analysis of the average (over the period of ATSR observations) days of the year on which the lake-mean LSWT drops below 1 °C and rises above 1 °C. Layden et al. (2015) define these as the 1 °C cooling and 1 °C warming days respectively, and observe good consistency with in situ measurements of ice-on and ice-off days for 21 Eurasian and North American lakes. Layden et al. (2015) also demonstrate the integrity of the ARC-Lake LSWTs on a global scale, through the strong relationship the observed LSWTs have with meteorological data (air temperature and solar radiation) and geographical features (latitude and altitude). On this basis, the ARC-Lake LSWT observations are considered reliable and suitable for use in this tuning study.

~~data. Validation of the observations was performed through a match-up data set of in situ temperature data consisting of 52 observation locations covering 18 of the lakes (MacCallum and Merchant, 2012). Furthermore, the 1 °C cooling and warming day, which is defined as the day of the year on which the average (over the period of observations) lake-mean LSWT drops to below 1 °C (1 °C cooling day) and rises to above 1 °C (1 °C warming day), show a good consistency with in situ measurements of ice-on and ice-off days for 21 Eurasian and North American lakes (Layden et al., 2015). Layden et al. (2015) also demonstrates the integrity of the ARC-Lake LSWTs on a global scale, through the strong relationship between the observed LSWTs and meteorological data (features of air temperature and solar radiation) and geographical features (latitude and altitude). On this basis, the ARC-Lake LSWTs are considered reliable and suitable for use in this tuning study.~~ An average of the day and night lake-mean LSWT observations from August 1991 to the end of 2010, are used to tune the model~~, retaining~~

~~the~~. The final year of observations (2011) is retained to carry out an independent evaluation on the tuned model. For 119 lakes, there are continuous LSWT observations for 20 years (all three ATSR instruments, from August 1991 to December 2011), 113 lakes have 16 years of continuous LSWT observations (2 ATSR instruments), and 14 lakes have 8–9 years of LSWT observations (1 ATSR instrument). The location of the 246 lakes (55° S to 69° N), classified by surface area, using polygon area in Global Lakes and Wetlands Database (Lehner and Döll, 2004), is shown in Fig. ~~2~~3.

2.2 Model; *FLake* lake model

FLake is a 1-dimensional thermodynamic lake model, capable of predicting the vertical temperature structure and mixing conditions of a lake. This model is a two-layer parametric representation of the evolving temperature profile of a lake and is based on the net energy budgets (~~Mironow~~Mironov, 2008). The lake conditions of the homogeneous “‘upper mixed ~~layer”~~layer’ (epilimnion) and the “‘bottom ~~layer”~~layer’ as represented in Fig. ~~3~~4, are modelled in *FLake*. *FLake* utilises the minimum set of input data required for 1-dimensional thermal and ice models~~;~~: meteorological forcing data (shortwave and long wave radiation, wind speed, air vapour pressure and air temperature), an estimation of turbidity and basic bathymetric data (Lerman et al., 1995). In *FLake*, the thermocline is parameterised through a self-similarity representation of the temperature profile. Although~~,~~ models based on the concept of self-similarity are considered to be only fairly accurate (Dutra et al., 2010), we show that modelled ~~biases~~mean differences between the model and observed LSWTs are greatly ~~reduced~~lowered by tuning the model.

2.2.1 Lake-specific model properties

As outlined in the introduction, optimisation of LSWT-regulating properties~~;~~ (lake depth (*d*), snow and ice albedo (*α*) and light extinction coefficient (*κ*~~),~~)), can greatly improve the LSWTs produced in *FLake*. ~~Values for other~~Other lake-specific properties ~~outlined in~~adjusted for this

~~section~~ study are ~~retained throughout the investigative and tuning process.~~

: c_relax_C~~: is~~, fetch, latitude and the starting conditions.

c_relax_C: a dimensionless constant used in the relaxation ~~time scale~~equation for the shape factor with respect to the temperature profile in the thermocline.

The default c_relax_C value of 0.003 was found to be too low to adequately readjust the temperature profile of deep lakes (G. Kirillin, personal communication, 2010), weakening the predicted stratification and affecting the LSWT. For lakes with mean depths < 5 m, the c_relax_C value is set to 10^{-2}, and decreases with increasing depth, to a setting of 10^{-5} for mean depths > 50 m, as recommended by G. Kirillin (personal communication, 2010).

Fetch: wind fetch is calculated as the square root of the product of lake length and breadth measurements. These measurements are available for 205 of the 246 lakes. The calculated fetch of these 205 lakes are found to be strongly related to surface area, Eq. (1), $R^2_{adj} = 0.84$, $p = 0.001$. Equation (1) is used to determine the fetch of the remaining 41 lakes with no available dimensions.

fetch = 39.9~~+~~ km + 0.00781 area km (1)

latitude: the latitude of the lake centre reference co-ordinates (Herdendorf, 1982; Lehner and Döll, 2004).

Starting conditions: these provide *FLake* with the lake-specific initial temperature and mixing conditions~~. Other than shortening the model spin-up time, the starting conditions showed no influence over the modelled LSWTs thereafter. The starting conditions are~~ : temperature of upper mixed layer, bottom temperature, mixed layer depth, ice thickness and temperature at air–ice interface. A good estimation of the starting conditions for each lake was obtained from the *FLake* model based on the hydrological year 2005/06 (Kirillin et al., 2011). Other than shortening the model spin-up time (to an average of < 3 days), the starting conditions showed no influence over the modelled LSWTs thereafter.

2.2.2 Fixed model parameters

The model parameters that remain fixed throughout the investigative and tuning ~~pro~~process, across all lakes (fixed model parameters) are icewater_flux, inflow from the catchment and heat flux from sediments. For icewater_flux, (heat flow from water to ice) G. Kirillin (personal communication, 2010) suggests values of ~ 3–5Wm^{-2}. In this study a value of 5Wm^{-2} is applied to all lakes. Inflow from the catchment and heat flux from sediments are not considered in this study.

~~cess, across all lakes (fixed model parameters) are icewater_flux, inflow from the catchment, heat flux from sediments and variation in the light extinction coefficient.~~

~~For icewater_flux, (heat flow from water to ice) G. Kirillin (personal communication, 2010) suggests values of ~ 3–5Wm~~$\cancel{^{-2}}$~~. In this study a value of 5Wm~~$\cancel{^{-2}}$ ~~is applied to all lakes. The inflow from the catchment and heat flux from sediments are not considered in this study. Variation (throughout the annual cycle) of light extinction coefficient is not considered. However, the effect of light extinction coefficient on LSWT, when its effect is most prominent (summer time) is considered, as discussed in Sect. 2.4.~~

2.2.3 Model forcing data

FLake is forced with ECMWF Interim Re-analysis (ERA) data (Dee et al., 2011; ECMWF, 2009), at the grid points closest to the lake centre (0.7° x 0.7° resolution), as shown in the Supplement. Mean daily values of the following parameters are used to force the model (shown in Table 1): shortwave solar downward radiation (SSRD), air temperature and vapour pressure at 2m, wind speed, and total cloud cover (TCC).

~~as shown in the Supplement. Shortwave solar downward radiation (SSRD), air temperature and vapour pressure at 2 m, wind speed and total cloud cover, in their mean daily values, as shown in Table 1 are used to force the model. As most long-term wind speed records are measured over land~~ ~~(U_{land})~~ ~~and are considered to underestimate the wind speed over water~~ ~~(U_{water})~~~~, scaling of the wind speeds is considered during the trials. For water bodies with fetches > 16m, Hsu (1988) recommends the scaling shown in Eq. (2). For bodies of water with fetch < 16m a scaling of 1.2 is considered reasonable (Resio et al., 2003). To find a suitable wind speed scaling, the trial work is carried out using the unscaled wind speed (*u1*), wind speed factored by 1.2 (*u2*), and wind speed suggested by Hsu (1988), *u3* (Eq. 2).~~

~~$U_{water} = 1.62+1.17U_{land}$ (2)~~

2.3 Tuning method

A suitable range of factors/values for *d*, ~~κ~~α and ~~α~~κ is determined through the model trials (carried out on 21 seasonally ice-covered lakes and 14 non-~~seasonally~~ ice covered lakes, Fig. ~~4~~5). The lakes used in the trials are chosen because they broadly represent the range of lake characteristics – lake depth, snow and ice albedo and light extinction coefficient – and have available Secchi disk depth data. Secchi disk depth data is used to derive light extinction coefficients values in the first trial (untuned model).

2.3.1 Light extinction coefficients for trial lakes

The light extinction ~~coefficients~~coefficient values for the untuned model trial are derived from

Secchi disk depth data ~~(~~, κ_{sd} (m^{-1}), obtained from the ILEC database (ILEC, 1999). Many studies have been carried out deriving κ values from Secchi disk depths (Poole and Atkins, 1929; Holmes, 1970; Bukata et al., 1988; Monson, 1992; Armengol et al., 2003). Five methods of relating κ values to Secchi disk depths are compared in Fig. ~~5~~6. This comparison covers a range of different water conditions, from coastal turbid waters (Holmes, 1970) and eutrophic water (tested 1 km from a dam in the Sau reservoir, Spain) (Armengol et al., 2003) to a range of North American lakes of different trophic levels (Monson, 1992).

For Secchi disk depths > 10 m, as shown in Fig. ~~5~~6, all methods show a reasonably good comparison between Secchi disk depths and κ. From Secchi disk depths of 10 to 1m the range of results between studies ~~become~~becomes increasingly large. Bukata et al. (1998) showed that the formula Eq. (~~3~~2), based on in situ optical measurements from many stations, adequately described Lake Huron, Lake Superior and Lake Ontario, for Secchi disk depths from 2 to 10 m;

$\kappa_{sd} = (0.757 \cancel{x} / S) + 0.07\,m^{-1}$ ~~+0.07 (3~~ (2)

where S = Secchi disk depth (m).

Of the 5 studies, this formula produces the 2~~0~~

lowest (most transparent) κ values, ~~and possibly~~potentially more ~~likely to represent~~ representative of open water conditions of large lakes, and is therefore used in this study~~.~~

~~For~~ for lakes with Secchi disk depths of 2-10 m. In the absence of a light extinction coefficient formula suitable for large lakes outside ~~the 2–10m~~ this Secchi disk depth range (less than ~~2m~~2 m and greater than 10 m~~)~~), the Poole and Atkins (1929) formula is applied. This formula, Eq. ~~(4), is used as~~

~~it is considered to serve as a universal relation between light extinction coefficient and~~

~~Secchi disk depth data and~~(3), provides sufficiently accurate estimations of light extinction coefficients in waters with all degrees of turbidity (Sherwood, 1974).

$\kappa_{sd} = 1.7$ ~~= Secchi disk depth (4~~ $/ S$ (3)

2.3.2 Light extinction coefficients for tuning of all lakes

Many lakes do not have available Secchi disk depth data. For this reason, an alternative approach is used to provide light extinction coefficients in the tuned model trials and for the tuning of all lakes. A range of 10 optical water types which essentially describe the attenuation process of ~~oceans~~ocean water and its changes with turbidity (Jerlov, 1976) is applied.

These consist of 5 optical water types for open ocean, type I, IA, IB, II and III; type I being the most transparent and type III being least transparent and 5 coastal ocean types (1, 3, 5, 7 and 9) (Jerlov, 1976). The ~~spectra~~spectre for these 10 ocean water types are divided

~~(~~ (in fractions of 0.18, 0.54, 0.28) into three wavelengths~~;~~: 375, 475 and ~~700 nm~~700nm, respectively. The 10 ocean water types are renamed herein as κ_{d1} to κ_{d10} the values for which are shown in Table 2.

2.3.3 Tuning of lake depth

Lake depth information was obtained from Herdendorf (1982), the ILEC World

Lake Database (http://wldb.ilec.or.jp/), LakeNet (http://www.worldlakes.org/) and (Kourzeneva et al., 2012). The mean depth (Z_{d1}) is the recommended depth value for *FLake*. Where only maximum depth is available (9 lakes), the mean depth is calculated using the average maximum-to-mean depth ratio of lakes with known maximum and mean depths. This ratio is 3.5 for seasonally ice-covered lakes and 3.0 for ~~nonseasonally~~ non-ice covered lakes. ~~Effective~~In the tuning process, depth ~~(Z_d)~~ factors (outlined in Table 2) are applied to the lake-mean depth. The tuned depth is referred to as the 'effective depth'.

~~depth (Z_{d1} : Z_{d6}), resulting in lake depths ranging from 0.3 to 2.5 times the mean depth,~~

~~Table 2.~~ For lakes with no depth information, the effective depth factors are applied to an initial ~~depth~~ of 5 m. If ~~a low~~the effective depth is ~~indicated (early~~too shallow, tuning is repeated using a deeper input depth. Early LSWT cooling and/or a high summertime LSWT ~~comparative to~~; July, August and September (JAS) LSWT, compared to the observed LSWT~~), tuning is repeated using a greater input depth.~~ are indications of an effective depth that is too shallow.

2.3.4 Tuning of snow and ice albedo

~~The~~ *FLake* uses two categories of albedo for snow (dry snow and melting snow) and two categories for ice (white ice and blue ice). As the snow cover module with *FLake* is not operational in this version of the model, the snow and ice albedo are set to the same default ~~snow and ice albedo (α)~~ value ~~is~~in the *FLake* albedo module, 0.60 for dry snow and white ice and 0.10 for melting snow and blue ice~~,~~. These default snow and ice albedo values are referred to as $\alpha 1$~~.~~ in this study. During the preliminary trials, a higher albedo (than $\alpha 1$) was shown to delay ice-off, substantially improving the timing of early ice-off, compared to observed LSWTs (demonstrated in Fig. 1a). A higher snow and ice albedo causes more of the incoming radiation to be reflected, resulting in a later ice-off. On ~~the~~this basis ~~of the modelled biases outlined~~

~~in the introduction~~, we apply 3 additional albedos of higher values ($\alpha 2$: $\alpha 4$), shown in Table 2, ~~when~~for tuning ~~of~~ seasonally ice-covered lakes. ~~A higher snow and ice albedo~~

~~causes more of the incoming radiation to be reflected, causing a later (and more timely) ice-off.~~ Albedo when discussed throughout this study refers to the albedo of snow and ice ~~albedo~~. The albedo of water (in liquid phase) is ~~not considered in this tuning study. and is~~ maintained at the default value of 0.07 throughout this study.

2.3.5 Wind speed scaling

~~Trial work~~Scaling of wind speeds is considered during the trials, as most long-term records of wind speed are measured over land (U_{land}) and are considered to underestimate the wind speed over water (U_{water}). For adjusting wind speeds (measured in m/s) over land to wind speeds over sea surfaces, Hsu (1988) recommends the scaling shown in Eq. (4). For bodies of water with fetch < 16 km a scaling of 1.2 is considered reasonable (Resio et al., 2008). To find a suitable wind speed scaling, the trial work is carried out using the unscaled wind speed (*u1*~~) and scaled~~), wind ~~speeds,~~

~~-~~speed factored by 1.2 (*u2*), and wind speed suggested by Hsu (1988), *u3*~~, as described in Sect. 2.2.3.~~ (Eq. 4). During the trial work, the most appropriate wind speed scalings are determined and are subsequently used in the tuning study.

$$U_{water} = 1.62 \text{ m/s} + 1.17 U_{land} \quad (4)$$

Where U_{water} = wind speed over water (m/s), and U_{land} = wind speed over land (m/s

2.3.6 Summary of the tuning of the LSWT-regulating properties

Table 2 contains a summary of the factors/values for *d*, ~~κ~~α and ~~α~~κ used in the tuning study. The tuning approach applied in this study provides an effective method for the tuning of LSWTs and overcomes the limitation of the lack of available lake characteristic information for many lakes. The model is tuned using the optimal combination of LSWT-regulating properties; 80 possible combinations for seasonally ice-covered lakes and

~~regulating properties; 80 possible combinations for seasonally ice-covered lakes and~~

60 possible combinations for non-~~seasonally~~ ice covered lakes.

2.4 Tuning metrics

The tuning metrics are the ~~biases~~mean differences (between the modelled and the observed LSWTs) which are used to quantify the effect that the LSWT-regulating properties have on the modelled LSWTs.

2.4.1 Tuning metrics for seasonally ice-covered lakes

The metrics and the effect of the LSWT-regulating properties on them, for seasonally ice-covered lakes is summarised in Table 3. The effect of light extinction ~~co-efficient effect~~ coefficient on the ~~summertime LSWT; July, August and September (~~JAS~~) LSWT~~ LSWTs is demonstrated in Fig. ~~6~~7, showing that the tuned light extinction coefficient (κ_d) value~~(~~, κ_{d6}~~)~~ in place of a lower (more transparent) κ_d value (κ_{d2}), described in Table 2, substantially improves the JAS LSWT~~.~~

, when compared to the observed LSWT. In this figure, the greater effect of light extinction coefficient on the maximum LSWT than on the minimum LSWT is also demonstrated. The effect that the tuned lake depth (effective depth) has on the 1 °C cooling day (the day the ~~lakemean~~

lake-mean LSWT drops below 1 °C; an indicator of ice-on) is demonstrated in Fig. ~~7~~8. The 1 °C warming day ~~is~~ (the day the lake-mean LSWT rises to above 1 °C; an indicator of ice-off~~).~~), is strongly influenced by snow and ice albedo, as demonstrated in Fig.1a. The daily MAD measures the daily mean absolute difference between the modelled and observed LSWTs. The closeness of the modelled and observed LSWTs is measured using these 4 metrics (normalized and equally weighted) and are the basis of selecting the optimal LSWT model for each lake.

2.4.2 Tuning metrics for non-~~seasonally~~ ice covered lakes

The metrics for non-~~seasonally~~ ice covered lakes are more difficult to ascertain, as there are no definitive stages in the LSWT cycle. For these lakes, the difference between the observations and model for the months where the minimum and maximum observed LSWTs occur (mth_{min} and mth_{max}) are applied as metrics. These metrics exert some control over temporally reconciling the ~~observed and~~ modelled monthly extremes~~.~~ with the observed monthly extremes. The daily MAD is also used to measure the daily mean absolute difference between the modelled and observed LSWTs.

2.4.3 Additional metrics for seasonally ~~and non-seasonally~~ ice-covered lakes and non-ice covered lakes

~~The~~ For each lake, the fraction of the observed mean LSWT variance over the number of years with observations, that is accounted for in the tuned model is used to help independently evaluate the tuned LSWTs. For non-ice covered lakes, the observed ~~LSWTs,~~ variance (K^2) over the length of the tuning period~~, the variance (K^2) in the month of minimum and maximum LSWT for non-seasonally ice covered lakes (var_{min} and var_{max}) and~~ is determined using var_{min} (and var_{max}): the mean LSWT for the month in which the minimum (and maximum) LSWT is observed. For seasonally ice-covered lakes, the variance is determined using var_{jas}: the variance in the observed mean JAS LSWT ~~for seasonally ice covered lakes (var_{jas}) is determined.~~ over the length of the tuning period. The fraction of these observed LSWT variances accounted for in the tuned model are quantified, ~~,~~ $inter_{min}$, $inter_{max}$ and $inter_{jas}$ (R^2_{adj}), respectively. The calculations to quantify var_{jas} and ~~$Inter_{jas}$~~ $inter_{jas}$ are shown in Eqs. (5) and (6).

var_{jas}: (K^2) observed JAS LSWT variance over the length of the tuning period;

$$var_{jas} = \sum (x_i^{obs\_jas} - \bar{x})^2 / (N - 1) \qquad (5)$$

~~***Inter*** **jas** (R^2 *adj*);~~where $^{obs\_jas}$ = observed mean JAS LSWT

$\bar{x}$ = mean across all years

N = number of years with JAS LSWTs

inter$_{jas}$: the fraction (R^2_{adj}) of the observed JAS LSWT inter-annual variance (var_{jas}) accounted for in the tuned model;

$$inter_{jas} = 1 - ((1 - r^2) (N - 1) / (N - P - 1)) \qquad (6)$$

~~N = sample size (number of years with JAS LSWTs)~~

P = total number of regressors

$$r^2 = \frac{N\sum (x_i^{obs\_jas}\, x_i^{mod\_jas}) - \sum (x_i^{obs\_jas}) \sum (x_i^{mod\_jas})}{(N\sum (x_i^{mod\_jas\,2}) - \sum (x_i^{mod\_jas})^2) (N\sum (x_i^{obs\_jas\,2}) - \sum (x_i^{obs\_jas})^2)}$$

where *mod_jas* = modelled JAS LSWT. The same Eqs. (5) and (6) are applied to determine $Inter_{max}$, var_{max}, $Inter_{min}$ and var_{min}, substituting “JAS” with “max” and “min”.

~~**2.4.4 Overview of tuning method**~~

~~An overview of tuning approach for seasonally and non-seasonally ice covered lakes is shown in Fig. 8.~~

where *obs_min* (and *mod_min*) = mean observed LSWT (and modelled LSWT) in the month where the minimum LSWT occurs, and

where *obs_max* (and *mod_max*) = mean observed LSWT (and modelled LSWT) in the month where the maximum LSWT occurs

3 ~~Applied~~ Trial results for wind ~~speeds~~speed scaling

Wind speed was examined in the untuned model trial for both seasonally ice-covered lakes and non ~~20~~

~~seasonally~~ -ice covered lakes. Wind speeds, *u1, u2 and u3* were modelled with untuned LSWT properties: mean lake depth (Z_{d1}), default snow and ice albedo ($\alpha 1$) and light extinction coefficient derived from Secchi disk depth data (κ_{sd}). The trials show that wind speed has a consistent effect on the modelled LSWT of seasonally ice-covered lakes. The higher wind speed scaling (*u3*) causes ~~an~~ earlier ~~(and more timely)~~ cooling and later ~~(and more timely)~~ warming~~,~~

(reducing the 1 °C cooling day and 1 °C warming day mean differences), lengthening the ice cover period and lowering the JAS LSWT, as demonstrated for Lake Simcoe ~~in Fig. 9.~~, Canada in Fig. 9. It is expected that the tuning of *d*, *α* and *κ*, with an applied wind speed of *u3*, will produce modelled LSWTs substantially closer to the observed LSWTs than those shown in Fig. 6, where tuning of *d*, *α* and *κ* is not applied. The more rapid mixing and heat exchange between the surface and atmosphere, as a result of the higher wind speed, causes an earlier modelled 1 °C cooling day. As wind promotes ice growth in the model, higher wind speeds also contribute to the later modelled 1 °C warming day. Wind speed scaling, *u3* in place of *u1*, for the trial seasonally ice-covered lakes, reduces the ~~bias~~mean difference in the length of the average cold phase (when compared to the observed cold phase) by ~~half~~~ 50% (from 39 to 21 days) and reduces the JAS ~~(July, August, September)~~ LSWT ~~bias~~mean difference by ~~half,~~~ 50%, from 3.71 to 1.87 °C, Table 4. On ~~this~~the basis of these trial results, the higher wind speed scaling, *u3* (U_{water} = 1.62+1.17U_{land}) is applied to all seasonally ice-covered lakes.

For non-~~seasonally~~ ice covered trial lakes, 5 of the 7 lakes at latitudes > 35° N/S show best results with *u3*, as demonstrated for ~~a lake~~Lake Biwa, located at 35.6° N, Fig. 10a. Five (5) of the 7 lakes located < 35° N/S show best results with *u1*, as demonstrated for ~~a lake~~Lake Turkana, located at 3.5° N, Fig. 10b. Of the scalings applied, there is no optimal wind speed scaling for all non-~~seasonally~~ ice covered lakes. This may be attributable to the highly variable range of latitudes, LSWTs and mixing regimes of non-~~seasonally~~ ice covered lakes.

For the remainder of the trials (tuned), for non-ice covered lakes, wind speed scaling, *u1*, was applied to lakes at latitudes < 35~~°~~ °N/S and *u3* to lakes at latitudes > 35~~°~~ °N/S ~~for non-seasonally ice covered lakes.~~. The metrics from the final set of trials (tuned using the range of d, κ and α factors/values outlined in Table 2) are shown in the second results column in Table 5. For both seasonally ice-covered lakes and non-~~seasonally~~ ice covered lakes, the target average MAD of < 1.0 °C is achieved for the trial lakes. As a result, this tuning approach is applied to all lakes.

4 Results

4.1 Summary of results

The average MAD and spread of differences (2σ) between the modelled and observed LSWTs for seasonally ~~and non-seasonally~~ ice-covered lakes and non-ice covered lakes, is reduced from 3.07 ± 2.~~55~~25 and 3.55 ± 3.20 °C for the untuned model ~~to 0.96 ± 0.63 and~~from 0.84 ± 0.51 and 0.96 ± 0.63 °C for the tuned model, Table 5.

These results demonstrate that the tuning process with the applied wind speed scalings can provide significant improvements on the untuned model~~,~~: run using the lake mean depth, light extinction coefficients derived from Secchi disk depth (as shown in Sect. 2.3.1) and ~~default~~ the model default

~~snow and ice~~ albedo (seasonally ice-covered lakes only~~) can be greatly improved by the tuning)~~.

~~process with the applied wind speed scalings.~~

The tuning method applied to seasonally ice-covered lakes is shown to be suitable for 135 of the 160 lakes, yielding an average MAD of 0.74 ± 0.48 °C, Table 6. The remaining 25 seasonally ice-covered lakes yielded comparatively poor results. These 25 lakes were re-tuned using ~~higher *d*~~greater effective depth factors and higher κ_d values, as outlined in the next sub-section (Sect. 4.1.1), yielding an average daily MAD of 1.11 ± 0.56 °C. Across the 160 lakes, an average MAD ~~(0.80 ± 0.56 °C, Table 5),~~ of below 1 °C was achieved~~.~~ (0.80 ± 0.56 °C, Table 5).

For non-~~seasonally~~ ice covered lakes, ~~the~~an average ~~daily MAD result for~~MAD of below 1 °C is again achieved (0.96 ± 0.66 °C) when 84 of the 86 lakes ~~is 0.96 °C, with a spread of differences of ± 0.66 °C (2σ),~~ are considered (Table 5~~, achieving an average MAD of below 1 °C. Two of the 86~~). However, the remaining two lakes ~~yield~~yielding highly unsatisfactory results.

The tuned values for the LSWT-regulating properties for all lakes and the tuning metrics are shown in the Supplement.

4.1.1 Seasonally ice-covered lakes

The average tuned metrics for 135 of the 160 lakes and the trial lakes are highly comparable, Table 6. For the remaining 25 lakes, the tuned metrics (not shown in Table 6) are comparatively poor~~;~~: the 1 °C cooling day was 14 days too early and/or the JAS LSWT mean difference value was ≥ 2 °C.

~~the 1 °C cooling day was ≥14 days too early~~

Relative to the size (depth and~~/or~~ area) of the ~~JAS LSWT value was ≥2 °C.~~

~~These 25~~ larger seasonally ice-covered lakes, these 25 lakes are shallow ~~lakes~~ (average mean depth < 5m) and small (18 of the 25 lakes are < 800 km^2). Twenty (20) of the 25 lakes are located in Eastern Europe or Asia, at relatively low altitudes; 22 of the 25 lakes are < 752 m a.s.l.. These 25 lakes were tuned to the highest depth factor,

~~Z_{d4}~~ Z_{d4} (1.5 times the mean depth) and/or the highest light extinction coefficient, κ_{d5} (lowest transparency). Although the transparencies for these 25 lakes are largely unknown, shallow lakes generally have poorer light transparencies than deeper lakes due to upwelling of bottom sediment. The shallow depth of the modelled lake (lower heat capacity) and the poor transparency of water (more heat retained in surface) were evident in the metric results; early 1 °C cooling day and/or high JAS LSWT values~~.~~ compared to the observed LSWTs. This indicates that ~~the~~ these lakes require a greater modelled depth to increase the heat capacity~~,~~ - postponing the 1 ~~°C~~°C cooling day - and lower transparency values (higher κ_d~~)~~)), causing less heat to be retained in the surface~~,~~

~~decreasing~~ and lowering the JAS LSWT. ~~A~~Consequently, the modified tuning ~~modification, using~~set-up, discussed below, was applied to these 25 lakes.

The tuning approach for these lakes is expanded to include 3 greater depth factors~~,~~

~~Z_{d5}:~~ of 2.5, 2 and 4 times the mean depth (Z_{d6}, Z_{d7}~~,~~ and Z_{d8}) and 2 higher light extinction coefficient values, κ_{d6} and κ_{d7} (Table 2~~) is applied.~~). This modification substantially improves the 1 °C cooling day and the JAS LSWT for these 25 lakes. A summary of the results are shown in Table 6 column 2. The tuning metrics results for the 160 lakes (using the modified tuning set-up for the 25 shallow lakes) are illustrated in Fig. 11.

4.1.2 Non-~~seasonally~~ ice covered lakes

The tuning metrics results for each of the 84 lakes are illustrated in Fig.12 and a summary of these results are shown in Table 5.

~~For 2~~Poor tuning results are observed for two of the 86 lakes~~,~~ (Lake Viedma and the Dead Sea~~, the difference~~). This is most likely due to differences between the altitude of the ERA T2 air temperature (geopotential height) and the lake altitude ~~is the~~.

~~most possible cause for poor tuning results.~~ Lake Viedma, an Argentinian freshwater lake of unknown depth, yielded a daily MAD of 3.1 °C ~~and~~. The Dead Sea, a deep and highly saline lake (340 g~~/l~~ L^{-1}) located in Asia at ~~404m~~404 m below sea level, yielded a daily MAD of 4.1 °C. For the Dead Sea, a temperature difference (in the month of maximum temperature) between the observed LSWT (33 °C) and ERA T2 air temperature (25 °C), results in a negative modelled ~~bias~~ mean difference of 6.3 °C in ~~the~~LSWT for this month ~~of maximum LSWT.~~. Given the standard air temperature lapse rate (6.5 °C km^{-1}), altitude can explain the substantially lower air temperatures. The altitude of Dead Sea ~~(~~(−404 m a.s.l.), is lower by ~ 850 m a.s.l. than the altitude of the meteorological data at the lake centre co-ordinates, 445 m a.s.l. (determined by interpolating surrounding cells using the orography data accompanying the ECMWF meteorological data).

~~the ECMWF meteorological data).~~

For Lake Viedma, while the observed LSWTs range from 5~~–~~ to 10 °C, the minimum ERA T2 air temperature remains well below 0 °C for many months of year, regularly reaching ~~-~~−8 °C, resulting in ~~the~~a negative modelled ~~bias~~ mean difference of 4.8 °C ~~in~~for the month of minimum LSWT. This ~~bias~~difference can be, at least, partially explained by the difference in altitude ~~of~~

~~>~~(> 500 m a.s.l~~.,~~.) between the altitude of Lake Viedma (297 m a.s.l.) and the altitude of meteorological data (825 m a.s.l.) at the lake centre co-ordinates ~~of 825 m a.s.l~~.

4.2 Tuning of saline and high altitude lakes

The results from the tuning ~~of~~approach applied to the 135 seasonally ice-covered lakes, the 84 non-ice covered lakes and the modified approach applied to the 25 shallow seasonally ice-covered lakes (described in Table 2) indicate that *FLake* is successful for tuning both saline and high altitude lakes, as well as freshwater and low altitude lakes~~, as~~. The tuned metrics categorized for saline, freshwater and low and high altitude lakes, are shown in Table 7 (seasonally ice-covered lakes) and in Table 8 (non-~~seasonally~~ ice covered lakes).

~~The~~Although the density of freshwater in *FLake* is determined at sea level (normal atmospheric pressure) (~~Mironow~~Mironov, 2008~~). At higher altitudes, the lower water density results in less~~

~~effective natural convective~~) and ~~thermal heat transfer processes. Although lake~~ the altitude

~~is~~ of lakes are not directly considered in *FLake*, ~~the effect of~~lake altitude (ranging from -12 to 5000 m a.s.l~~.,)~~., over the 246 lakes) is considered indirectly through the altitude of the meteorological forcing data (ERA) at the lake centre co-ordinates.

~~on LSWT is shown to be minimal or else compensated for by the tuning process.~~ The majority of the high altitude lakes are also saline; 7 of the 10 non-~~seasonally~~ ice covered lakes and 12 of the 14 seasonally ice-covered lakes. The comparability between observed and modelled LSWTs for two high altitude lakes (> 1500 m a.s.l.) are shown in Fig. 13.

4.3 Independent evaluation

Two methods are used to independently evaluate the tuned model.

1. ~~1.~~ The fraction (R^2_{adj}) of observed LSWT variance that is detected in the tuned model is quantified~~.~~; $inter_{min}$ and $inter_{max}$ (non-ice covered lakes) quantifies the observed variance (K^2) in the month in which the minimum LSWT (var_{min}) and maximum LSWT (var_{max}) occurs and $inter_{jas}$ (seasonally ice-covered lakes) quantifies the observed variance (K^2) in the mean JAS LSWT (var_{jas}).
2. ~~2.~~ The metrics for 2011 (observed LSWTs from 2011 were not used in tuning process) are compared with metrics from 2 tuned years.

4.3.1 Variance detected in the tuned model

~~The fraction of observed LSWT variance, , $\boldsymbol{var_{min}}$ and $\boldsymbol{var_{max}}$ for non-seasonally ice covered lakes and $\boldsymbol{var_{jas}}$ (K^2) for seasonally ice covered lakes, that is detected in the tuned model, , $\boldsymbol{inter_{min}}$, $\boldsymbol{inter_{max}}$ $\boldsymbol{inter_{jas}}$ ($R^2{}_{adj}$) is determined as shown in Sect. 2.4.3.~~ The results show that the modelled LSWTs capture less of the true (observed) inter-annual ~~variability~~variance in lakes where the observed LSWT variance and the annual LSWT range is

low. This indicates that lower latitude lakes and high altitude lakes are less well ~~repre~~represented in the model, than lakes with greater observed LSWT variance and the annual

~~sented in the model, than lakes with greater observed LSWT variance and the annual~~

range. This would also indicate that lakes in the Southern ~~hemispheric lakes~~Hemispheric at 35–55° S are less

well represented than lakes in the Northern Hemisphere at the same latitude, as the annual LSWT range is considerably lower at 35–55° S than at 35–55° N (Layden et al., 2015).

For non-~~seasonally~~ ice covered temperate lakes, the $inter_{max}$ and $inter_{min}$ fraction is substantially greater (0.49 and 0.37) than in tropical lakes (0.07 and 0.13), Table 9. This can be explained by the greater observed ~~variability~~variance (var_{max} and var_{min}) in temperate lakes (0.65 and 0.69 K^2), than in tropical lakes (0.12 and 0.15 K^2). Across all non-~~seasonally~~ ice covered lakes var_{max} and $inter_{max}$ show a correlation of 0.69 and var_{min} and $inter_{min}$ show a correlation of 0.33 (p < 0.05), showing that lakes with greater observed ~~variability~~variance have a greater portion of the ~~variability~~variance detected in the model. For high altitude seasonally ice-covered temperate lakes, the fraction of the observed JAS LSWT inter-annual ~~variability~~variance explained by the tuned model is considerably less ($inter_{jas}$ = 0.21) than for low altitude lakes (0.52), Table 9. The variability in the observed JAS LSWT for high altitude lakes (var_{jas} = 0.19) is almost 4 times lower than for low altitude lakes (0.75). For seasonally ice-covered lakes the $inter_{jas}$ and var_{jas} are also correlated, 0.31, p ~~=~~≤ 0.~~000~~0005. Furthermore, the annual range of monthly LSWTs for non-~~seasonally~~ ice covered lakes, explain 0.38 and 0.36 (p ~~=~~≤ 0.~~000~~0005) of the variation in var_{max} and var_{min}, with lakes of a low annual range (high altitude and tropical lakes), showing less inter-annual ~~variability~~variance. This supports the findings that tropical and high altitude lakes are less well represented in the model.

~~The relationship between the annual range and var_{jas} is not detected in seasonally ice covered lakes. This is most possibly because the inter-lake variance in the annual range of monthly LSWTs is almost 3 times less (22 K^2) than in non-seasonally ice covered lakes (62 K^2). The greater inter-lake variance in the annual monthly LSWTs of non-seasonally ice covered lakes can be attributed to the greater range in latitudes (48° N to 55° S) and the absence of a minimum LSWT restriction due to ice cover.~~

4.3.2 Comparison of tuned and untuned model LSWTS

The tuning period extends from 8 August 1991 to 31 December 2010. The final year (2011) of available observational ARC-Lake LSWT data is used to independently evaluate the tuning process. The tuned model is forced for the year 2011 and the tuned metrics are quantified. The metrics of this untuned year (2011) are compared with metrics from two tuned years (1996 and 2010), as shown in Tables 10 and 11. The year 1996 is the first full year of data from ATSR2 and 2010 is the last year of tuned data from Advanced ATSR (AATSR).

~~metrics are quantified. The metrics of this untuned year (2011) are compared with metrics from two tuned years (1996 and 2010), as shown in Tables 10 and 11. The year 1996 is the first full year of data from ATSR2 and 2010 is the last year of tuned data from AATSR.~~

The mean metric results and the spread of differences across the 135 seasonally ice-covered lakes ~~for the tuned and untuned period~~ are highly comparable across all 3 years~~,~~ ~~showing~~ of the tuned and untuned periods, with marginally better MAD metrics observed for the untuned period. For the 25 shallow lakes tuned with the modified ~~approach~~tuning set-up, the MAD results for the untuned year are more comparable with 2010 results than the 1996 results.

For the other 3 metrics for the 25 shallow lakes, the untuned year has a lower spread of differences across lakes than for 2010~~and a marginally better~~. Marginal improvements are also seen in the JAS LSWT and 1 °C cooling day. The spread of differences across lakes for 1 °C warming day for the untuned year is wider than in 2010 but is better than for 1996. The 1 °C cooling and warming day ~~biases~~mean differences for 1996 and 2010 are less comparable for the 25 lakes than for the 135 lakes. This may be because the modelled effect of depth on the metrics ~~are~~

is more predictable for deeper lakes, as illustrated in Fig. 16, than for shallow lakes.

~~Overall, the result~~

Although inter-annual variance may somewhat obscure year-on-year comparisons, the results of the modelled LSWTs for the untuned year (2011) compare well to the modelled results from the tuned years (1996 and 2010) showing that the model remains stable when run with ERA forcing data outside the tuning period. For non-~~seasonally~~ ice covered lakes, although the mean MAD and dispersion of errors is slightly higher for the untuned year, 2011, Table 11~~. However~~, overall, the metrics are very comparable to the metrics from 1996 and 2010.

5 Findings and discussion

5.1 The effect of the 1 °C warming day on JAS LSWT

Through the trial work, the effect of the timing of the 1 °C warming day (indicative of ice-off) on the JAS LSWT and on the timing of the 1 °C cooling day (indicative of ice-on) ~~of~~

is demonstrated, for deep high latitude or very deep seasonally ice-covered ~~trial~~ lakes ~~is demonstrated.~~

. Using the default snow and ice albedo ($\alpha 1$, Table 2), the modelled 1 °C warming day of the 21 trial lakes occur, on average, 20 days too early. ~~A higher albedo ($\alpha 2$, Table 2) delays the 1 °C warming day by 27 ±12.6 days and decreases the mean JAS LSWT bias by half,~~

A higher albedo ($\alpha 2$, Table 2) delays the 1 ºC warming day by 27 + 12.6 days and decreases the mean JAS LSWT mean difference by ~50%, to 0.98 + 2.51 ºC, across the 21 lakes. There is no correlation between the modelled JAS LSWT decrease and the length of the delay in the 1 ºC warming day (due to the increased snow and ice albedo) over the 21 lakes. This indicates that the JAS LSWT of the lakes do not respond in the same manner to changes in the 1 ºC warming day. Lake depth and latitude ~~cause~~were found to account for much of the modelled ~~inter-lake~~

~~variability between the length of~~variance in the JAS LSWT decrease (caused by the ~~delay~~changes in the 1 ~~°C~~ºC warming day ~~and the JAS LSWT~~

~~decrease.~~). Across the 21 lakes~~,~~ together (using stepwise regression), ~~they~~lake depth and latitude account for 0.50 (R^2_{adj}, p = 0.001) of the variance~~.~~ in the JAS LSWT decrease. Separately, depth accounts for 0.35 (p = 0.003) and latitude for 0.26 (p = 0.01) of the variance. The LSWTs for Great Bear and Great Slave lakes modelled with $\alpha 2$ (high) and $\alpha 1$ (low; default) snow and ice albedo albedos shown in Fig. 14, clearly show the effect that the later warming day has on the modelled JAS LSWT. Great Slave (62° N and 41 m in depth) and Great Bear (66° N and 72 m in depth), show a JAS LSWT decrease of 4.26 and 3.40 °C as a result of a 28 and 32 day delay in 1 °C warming day. The effect of changes in the 1 °C warming day on the JAS LSWT is only evident in deep lakes; a delay of 29 and 32 days in the 1 °C warming day for Winnebago (44° N) and Khanka (45° N) both with depths of 5 m, resulted in only a small JAS LSWT decrease of ~0.1 °C. In Fig. 15, the lake-mean depth of the 21 trial lakes are plotted against latitude. The relationship between the depth and latitude of the lakes and the change in the JAS LSWT caused by the later 1 °C warming day (due to the higher albedo), is shown in this figure, by use of coloured circles. This figure shows that for deep high latitude lakes the decrease in the JAS LSWT (presented as the decrease in the JAS LSWT, per week of later 1 °C warming day, ~~shown in Fig. 15, demonstrates the greater JAS LSWT change for deeper higher~~°C week^{-1}), is more pronounced than for shallow low latitude lakes.

This finding is supported by a study on Lake Superior, average depth of 147 m, (Austin and Colman, 2007). A JAS LSWT warming trend (of 2.5 °C from 1979 to 2006) for Lake Superior which is substantially in excess of the air temperature warming trend, was found to be as a result of a longer warming period, caused by an earlier ice-off date of ~0.5 day yr^{-1}.

The modelled results also show that depth explains 0.42 (R^2_{adj}, p = 0.001) of the inter-lake variance in the response of the 1 °C cooling day to the decrease in the JAS LSWT. The modelled decrease in the JAS LSWT causes an earlier 1 °C cooling day in deep lakes. For Great Slave (41 m), a decrease of 4.26 °C in the modelled JAS LSWT resulted in ~~an earlier~~the 1 °C cooling day ~~of~~occurring 3.4 days earlier. The effect is bigger for deeper lakes. For Great Bear (72 m), the JAS LSWT decrease of 3.40 °C causes an earlier 1 °C cooling day ~~of~~, by 7.6 days. For the deepest lake in the trials, Lake Hovsgol (138 m) the JAS LSWT decrease of 2.60 °C had the largest effect on 1 °C cooling day, causing it to occur 12.8 days earlier.

The findings are sensible. A delay in the 1 °C warming day, shortening the lake warming period, may not prevent a shallow lake reaching its full heating capacity but may prevent ~~of~~ a deep lake from reaching its maximum heat storage capacity. At higher latitudes, the LSWT warming period for northern hemispheric lakes ~~become increasingly~~becomes increasingly short (Layden et al., 2015). As a result, deep lakes increasingly fall short of reaching their maximum heat storage, causing a larger JAS LSWT decrease. Any changes to the 1 °C warming day of deep and high latitude (or high altitude) lakes will therefore affect JAS LSWT. Deep lakes also cool more slowly than shallow lakes, resulting in a later cooling day.

~~short (Layden et al., 2015). As a result, deep lakes increasingly fall short of reaching their maximum heat storage, causing a greater JAS LSWT decrease. Any changes to the 1 °C warming day of deep and high latitude (or high altitude lakes) will therefore affect JAS LSWT. Deep lakes also cool more slowly than shallow lakes, resulting in a later cooling day.~~

These findings highlight the sensitivity of the whole LSWT cycle of deep high latitude lakes, to changes in the timing of the 1 °C warming day, as illustrated in Fig. 16. This figure also illustrates how an earlier 1 °C cooling day caused by a lower JAS LSWT may be counteracted or masked in deep lakes, where heat is retained during the cooling period.

The effect that depth has on the JAS LSWT is apparent when comparing lakes at the same altitude and latitude but with different depths. ~~For example, Lake Nipigion, located~~ For example, Lake Nipigion and Lake Manitoba, both located in Canada (50 °N and 51 °N) and at similar altitudes (283 m a.s.l. and 247 m a.s.l) have considerably different depths, 55 m and 12 m respectively. Significant differences are observed in JAS LSWT for these lakes, the deeper lake having an average JAS LSWT 4.4 °C lower than that of the shallower lake (15.4 °C compared to 19.8 °C).

~~in Canada at 50° N and at 283 m a.s.l., has a mean depth of 55m and an average JAS~~

~~LSWT of 4.4 °C lower (15.4 °C) than that of Lake Manitoba (19.8 °C), also located in Canada (at 51° N and 247 m a.s.l.), but with a mean depth of only 12m.~~

~~There is a~~

As the snow cover module with *FLake* ~~which~~ is not operational in this version of the model~~, therefore~~; the insulating effect that snow has on the underlying ice is not modelled. As a result the snow and ice albedo are set to the same default value (0.60), possibly underestimating the extent of the albedo effect of snow. This may be the reason for the earlier 1 ~~°C~~ $^{\circ}$C warming day and the higher JAS LSWTs, when modelled with the default ~~snow and ice~~ albedo. As shown in the tuning process, a higher albedo results in a later ~~(and more timely) 1 °C~~ 1 $^{\circ}$C warming day (reducing the mean difference between the modelled and observed LSWTs) and as a result, reduces the period of time of the surface absorption of short-wave radiation, improving the mean JAS LSWTs. It is possible that the icewater_flux value of 5~~.~~ W/m^{-2} may be an overestimation of the water-to-ice heat flux in the ice growth phase of deep and shallow lakes. This greater heat flux, leading to underestimated ice thickness, could have contributed to the large 1 $^{\circ}$C warming day mean difference shown in table 5 (column 1). In a study by Malm et al. (1997), the water-to-ice heat flux during the ice growth phase was shown to be < 1 W/m^{-2} in both deep (15-20 m) and shallow lakes. Underestimated ice thickness, causing an early ice melt, may possibly have led to over-tuning of albedo in the tuned model.

5.2 Lake-bottom temperatures modelled in *FLake*

The month of minimum LSWTs in the annual cycle (monthly minimum) have the potential to be used as a proxy for determining the temperature of the bottom layer (hypolimnion) of non-~~seasonally~~ ice covered lakes. The monthly minimum climatological ARC-Lake LSWT explains 0.97 (R^2_{adj}) of the inter-lake variance in the bottom temperatures, obtained from the *FLake* model based on the hydrological year 2005/2006 (Kirillin et al., 2011) and have a ~1:1 relationship, as shown in Fig. 17. Although *FLake* is a two-layer model; the depth of the hypolimnion layer is not calculated, the bottom modelled temperature is representative of the hypolimnion temperature, which remains constant with depth.

~~2011) and have a 1:1 relationship, as shown in Fig. 17.~~ Empirically, it has previously ~~being~~ been shown that from the equator to approximately 40° (N/S), the steep decline in the minimum LSWT is reflected in the hypolimnion temperature (Lewis, 1996). This relationship is applicable to deep stratified non-ice covered lakes. For these lakes, the surface water, when at its coolest in the annual cycle (minimum LSWT) and therefore its densest, sinks to the lake-bottom. During the summer stratification period, the water in the upper mixed layer is warmer and less dense and therefore remains in the upper layer (with exception to high wind or storm conditions, which can induce intense vertical mixing). The strengthened density gradient in the summer thermocline (as demonstrated for Lake Malawi in Fig. 4) also protects the hypolimnion from heat flux through the lake surface. As a result, the lake hypolimnion temperature of deep non-ice covered lakes can reflect the minimum LSWT. The comparability between the monthly minimum LSWT (using the ARC-Lake monthly minimum climatology LSWTs) and the bottom temperature, for all deep (> 25 m) non-~~seasonally~~ ice covered lakes (14 lakes) supports this empirical observation~~.~~ (Fig. 17).

Although~~,~~ changes in other factors affect hypolimnion temperature, such as ~~influx~~influx of cooler water and geothermal heating, the monthly minimum LSWTs from ~~satellite~~satellites can offer a good indication of hypolimnion temperature; useful in cases where this otherwise can not be or ~~isn't~~aren't observed directly.

5.3 Wind speed scaling for low latitude lakes

The trials showed that while non-~~seasonally~~ ice covered lakes at latitudes < 35~~°~~ °N/S required no wind speed scaling ($u1$), the largest wind speed scaling ($u3$) improved LSWTs for non-~~seasonally~~ ice covered lakes at latitudes > 35~~°~~ °N/S and all seasonally ice-covered lakes ~~produced more representative LSWTs~~

~~using the largest wind speed scaling (*u3*)~~ , as outlined in Sect. ~~2.2.~~3.

For the deep (> 25 m) non-~~seasonally~~ ice covered lakes (14 lakes), the density difference between the lake surface (in the month of maximum LSWT) and the hypolimnion ~~temperature~~ during the summer stratification period

~~were~~ (when the density gradient of the thermocline is strongest, as illustrated in Fig. 4) was calculated (Haynes, 2013). The density ~~difference for~~ gradient of the thermocline is dependent on the temperature difference between the lake surface and the hypolimnion. For lakes at latitudes below 35~~°~~ °N/S ~~is~~ , the average density difference between these two layers is substantially lower (0.352 x 10~~kg~~$^{-3}$kg/m^{-3} ~~m3~~) than for lakes at latitudes above 35~~°~~ °N/S (1.183 x 10~~kg~~$^{-3}$kg/m^{-3} ~~m3).~~). This is due to the smaller annual temperature range of the lower latitude lakes.

It is possible that the ~~greater~~large density difference between ~~these two layers (~~the lake surface at maximum LSWT and the hypolimnion~~)~~ in ~~higher~~high latitude lakes during the stratification period, may produce a ~~stronger buffering effect~~buffer against wind~~, than for lakes with a smaller density difference~~

~~between the two layers.~~

induced mixing and therefore lessen the heat flux through the thermocline. As winds can drive lake mixing in deep lakes, it strongly influences the epilimnion depth and the LSWT. The larger the temperature (and density) gradient between the ~~maximum LSWT~~

lake surface and the hypolimnion during stratification, the more wind energy is required to produce the same amount of mixing than for lakes with a smaller temperature (and density) gradient between the two layers. Although the density differences between the two layers are considered in *FLake*, the ~~wind forcing data purports to *U*land~~model is forced with over land wind speed measurements. It is possible that when forced with an underestimated wind speed, the effect of wind on the LSWT will be further reduced. As a result, higher latitude lakes may show more representative LSWTs using a higher wind speed scaling, as discussed in Sect. 6.

5.4 Improving modelled LSWTs in *FLake*

The optimal LSWT-regulating properties of the 244 lakes provide a guide to improving the LSWT modelling in *FLake* for other lakes, without ~~needing~~having to tune the model for each lake separately.

5.4.1 Depth

The tuning results show that deep lakes are generally tuned to a ~~lower~~ shallower effective depth and shallower lakes to a ~~greater~~deeper effective depth. Figure 18 shows the relationship between the ~~lakemean~~ lake-mean depth and the effective (tuned) depth of all 244 successfully tuned lakes, colour coded by the effective depth factor optimised in the tuning process. The figure legend shows ~~the~~ ~~decrease in~~that the effective depth factor decreases with increasing average lake depth (also graphed in the figure insert), providing a means to estimate an appropriate effective depth for any lake with a mean depth from 4–124 m.

The tuned lake depths are sensible. For shallow lakes, tuning to a ~~greater~~deeper effective depth may compensate for not having considered the “‘heat flux from ~~sediments”~~sediments’ scheme in the model. ~~The retention~~Retention of heat in the sediments of a lake has the same effect as deepening the ~~lakes~~lake, causing an increase the heat storage capacity~~, which has been demonstrated (Fig. 1b) to reduce the maximum LSWT and delay the 1 °C cooling day~~.

Many deep lakes have 3 distinct layers, the upper mixed layer (epilimnion), the underlying thermocline (metalimnion) and the bottom layer (hypolimnion). As *FLake* is essentially a two-layer model, it is possible that for deep lakes the mean depth (mean of entire lake depth) is tuned to a shallower effective depth as it is more representative of the mean depth of the 2 upper lake layers. Other factors affecting the rate at which heat is exchanged between the atmosphere and the surface water, such as topography, altitude, bathymetry and surface area are not considered in *FLake.* As these factors vary considerably between lakes, it is possible that lake depth tuning may also compensate for the effect that these factors have on the rate of the surface heat exchange.

5.4.2 Light extinction coefficient

Across all lakes, 57% were tuned to light extinction coefficient values of ~~either _d4~~κ_{d4} or κ_{d5}. These lakes are globally distributed and have a wide range of mean depths (1-138 m) with an average mean depth of 16 m. In view of this finding and considering that light extinction coefficient values are scarce for the majority of lakes, we assess if κ_{d4} and κ_{d5} can be used to provide a good estimation of the light extinction coefficient for modelling LSWTs in *FLake*.

~~and κ_{d5}. The average depth of lakes tuned to _d4 is 21 and 13m for lakes tuned to κ_{d5}. Tuning of deeper lakes to the more transparent of these two κ_d value (κ_{d4}) and shallower lakes to the less transparent value (κ_{d5}) makes sense as water clarity of a shallower lake is more affected by the lake bottom sediments than that of deeper lake. In view of this finding and considering that light extinction coefficient values are scarce for the majority of lakes, we assess if κ_{d4} and κ_{d5} can be used to provide a good estimation of the light extinction coefficient for modelling LSWTs in *FLake*.~~

The untuned model is forced using two sets of light extinction coefficient values and the MAD results are compared. In the ~~first~~first model run, the average κ_{sd} value (derived from

Secchi disk depth data) of the trial lakes of each lake type is applied to all lakes of corresponding type. For the 21 seasonally ice-covered trial lakes, κ_{sd} = 0.82~~, is applied to all seasonally~~ ; for the 14 non-ice covered ~~lakes and the average ksd of the 14 trial non-seasonally ice covered lakes,~~ trial lakes, κ_{sd} = 1.46~~, is applied to all non-seasonally ice covered lakes.~~. In the second run, the model is forced with κ_{d4} ~~applied~~or κ_{d5} values. κ_{d4} is applied to all lakes > 16 m in depth (the average depth of lakes tuned with κ_{d4} or κ_{d5}) and κ_{d5} to all lakes ~~> 16m in depth and with κ_{d5} for all lakes~~ < 16m in depth. It makes practical sense to apply the less transparent of these two κ_d values (κ_{d5}) to shallower lakes, as shallow lakes are generally more affected by lake-bottom sediments than deeper lakes.

For both model runs the default ~~snow and ice~~ albedo and the mean depth are applied~~ and~~, while all other model parameters are kept the same. A comparison of the two model runs~~,~~ ~~show~~ shows that when LSWTs are modelled with κ_{d4} and κ_{d5} values, the daily MAD is reduced from 3.38 $\pm$ 2.74 to 2.28 $\pm$ 2.30 °C (33% decrease the average MAD). This indicates that in the absence of available light extinction coefficient values, application of κ_{d4} and κ_{d5} values may improve the modelling of LSWTs of large lakes in *FLake.*

~~*FLake.*~~

5.4.3 Snow and ice albedo

For seasonally ice-covered lakes, only 19% of the lakes were tuned to the default snow and ice albedo, $\alpha1$, (snow and white ice = 0.60 and melting snow and blue ice = 0.10). ~~64% of lakes were tuned to two higher albedos $\alpha2$ or $\alpha3$, (snow and white ice = 0.80 and~~Sixty four (64) % of lakes were tuned to two higher albedos $\alpha2$ or $\alpha3$, (snow and white ice = 0.80 and melting snow and blue ice = 0.60 for *α2* or 0.40 for *α3*), indicating that the default snow and ice albedo may be too low for the majority of lakes. In the absence of lake-specific snow and ice albedo information, the albedo value *α3* (snow and white ice = 0.80, melting snow and blue ice = 0.40) may provide a good estimate. The *α3* values are highly comparable to albedo values measured on a Lake in Minnesota using radiation sensors, where the mean albedo of new snow was shown to be 0.83 and the mean ice albedo (after snow melt) was 0.38 (Henneman and Stefan, 1999).

~~melting snow and blue ice = 0.60 for *α2* or 0.40 for *α3*), indicating that the default snow and ice albedo albedo is too low. To obtain a more timely (later) ice-off and to help address the overestimated JAS LSWTs, the albedo value *α3* (snow and white ice = 0.80, melting snow and blue ice = 0.40) is recommended in place default value (*α1*). The *α3* values are highly comparable to albedo values measured on a Lake in Minnesota using radiation sensors, where the mean albedo of new snow was shown to be 0.83 and the mean ice albedo (after snow melt) was 0.38 (Henneman and Stefan, 1999).~~

6 Summary and conclusions

The 1-dimensional freshwater lake model, *FLake*, was successfully tuned for 244 globally distributed large lakes (including saline and high altitude lakes) using observed LSWTs (ARC-Lake), for the period 1991 to 2010. This process substantially improves the measured ~~biases~~mean differences in various features of the lake annual cycle ~~(including saline and high altitude lakes), as summarised in Table 5~~, using only 3 lake properties (depth, snow and ice albedo and light extinction coefficient~~).~~

), as summarised in Table 5. In the process of tuning the model, we demonstrate several aspects of LSWT behaviour, in a way that cannot be done using the LSWT observations alone. We demonstrate the dependency of the whole modelled LSWT cycle of deep high latitude or high altitude lakes, on changes in the timing of the 1 °C warming day (indicative of ice-off). The monthly minimum LSWTs from satellites are demonstrated to offer a good indication of the modelled lake-bottom temperature, with a 1:1 relationship shown (Fig. 17). This is highly useful where the lake-bottom temperature can not be or aren't observed directly.

~~the dependency of the whole modelled LSWT cycle of deep high latitude or high altitude lakes, on changes in the timing of the 1 °C warming day (indicative of ice-off).~~ The ~~monthly minimum LSWTs from satellite are demonstrated to offer a good indication of the modelled lake bottom temperature (1:1), Fig. 17. This is highly useful where lake bottom temperatures can not be or isn't observed directly.~~

~~By determining the~~ amount of observed inter-annual LSWT variance (in the month in which the minimum LSWT and maximum LSWT occurs for non-ice covered lakes and in the JAS LSWT for seasonally ice-covered lakes), detected in the tuned model~~, it~~ was quantified. It can be concluded that lakes at lower latitude and high altitude ~~lakes (~~(for all lakes where the observed LSWT variance ~~and~~is low and for non-ice covered where the annual range is low) are less well represented in the model, than lakes with greater observed LSWT variance and ~~the~~ annual range.

We found that wind speed with no scaling, *u1*, is most appropriate for lakes at lower latitudes, < 35° N/S, and that wind speed with the largest scaling (*u3*; $U_{water} = 1.62 + 1.17U_{land}$), is most appropriate for lakes at higher latitudes > 35° N/S. ~~A greater wind~~A greater resistance to wind induced mixing and heat flux through the thermocline, as a result of a greater density gradient between the lake surface and the hypolimnion of high latitude lakes, may explain the suitability of the largest scaling for these lakes and the suitability of no scaling for low latitude lakes.

~~speed scaling for high latitude lakes may be required to overcome a greater buffering effect possibly caused by a greater temperature and density difference between the maximum LSWT and the hypolimnion during stratification than in low latitude lakes.~~

The optimal LSWT-regulating properties ~~of~~ (effective depth, snow and ice albedo and light extinction) for the 244 lakes are shown to be sensible and may provide a guide to improving the LSWT modelling in *FLake* for other lakes, without having to ~~tune~~ apply a tuning process to the model, requiring access to reliable observed LSWT information.

The relationship between the lake-mean depth and the effective (tuned) depth of all 244 successfully tuned lakes, show that deep lakes are generally tuned to a lower depth and shallower lakes to a greater depth. Figure 18~~,~~ provides a means to estimate an appropriate effective depth for any lake with a mean depth from 4–124 m. An albedo value $\alpha 3$ (snow and white ice = 0.80, melting snow and blue ice = 0.40) is recommended in place of the default value ($\alpha 1$). Where κ values are unknown, applying κ_{d4} for lakes > 16 m in depth and κ_{d5} for lakes < 16 m in depth improves the modelled LSWT.

This paper predominantly focused on the tuning of *FLake* and interpretation of the LSWT annual cycle using the tuned model. The tuned model is forced with ERA data over the available time span of LSWT observations (16–20 years~~),~~) but has the potential to be forced with ~~the complete~~ ERA data covering a longer time span ~~of available~~ (ERA data~~,~~ are available for a period of > 33 years; 1979–2012~~.~~). This offers the potential to provide a better representation of LSWTs changes over a longer period of time, as satellite observations for the relatively short period may reflect some inter-annual ~~variability rather the true changes.~~

variance. As demonstrated, the use of remote sensing and modelled LSWTs together extend the reliable quantitative details of lake behaviour beyond the information from either remote sensing or models alone. The ARC-Lake dataset has since been extended to include ~1000 smaller lakes (surface area > 100 km^2) worldwide, offering the potential to further quantify aspects of lake behaviour worldwide.

~~remote sensing or models alone. The ARC-Lake dataset has since been extended to include _ 1000 smaller lakes (surface area > 100 km2) worldwide, offering the potential to further quantity aspects of lake behaviour worldwide.~~

The findings in this study are expected to be of interest to limnologists concerned with the relationship between certain features of the LSWT cycle and lake characteristics. Limnologists may also benefit from other aspects of this study, for example, the effect of wind speed scaling on LSWTs and how the observed minimum monthly LSWTs may be used to estimate lake-bottom temperatures. The optimal LSWT-regulating properties of the 244 lakes may provide a guide to current and prospective users of *FLake* for improving the LSWT modelling in *FLake* for other lakes, without having to tune the model for each lake separately. This is of particular use for lakes where lake characteristic information is not available. The described approach to this study can provide practical guidance to scientists wishing to tune *FLake* to produce reliable LSWTs for new lakes.

Code availability

The code for the *FLake* model can be obtained from the following website; http://www.flake.igb-berlin.de/sourcecodes.shtml

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History

Version: 1.00 Date: 17 November 2005

Modification comments:

In the MODULE flake_parameters where the values of empirical constants of the lake model *FLake* and of several thermodynamic parameters are set, the ~~“~~‘temperature of maximum density of fresh ~~water”,~~water’, tpl_T_r, = 277.13 K (3.98 °C).

In the SUBROUTINE flake_driver (flake_driver.incf), the model uses a number of algorithms to update the bottom temperature, for example its relationship with mixed layer depth. As *FLake* is intended for cold water lakes, if the bottom temperature shows no relationship with the mixed layer depth, the models sets the lake bottom temperature to the temperatures of maximum density (3.98 °C). This creates a problem when modelling tropical lakes; it causes the model to spin up to a wrong “attracter”. This problem manifested itself in both the temperature profile and the mixed layer depth.

To overcome this problem, the lake-bottom temperature for non-~~seasonally~~ ice covered lakes in August; Southern Hemisphere winter, was used to set to the temperature of maximum density, before compiling and running the model.

~~lakes in August; tropical winter, was used to set to the temperature of maximum density, before compiling and running the model.~~

Language: Fortran 90. Software Standards: ~~“~~‘European Standards for Writing and Documenting Exchangeable Fortran 90 ~~Code”.~~Code’.

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Author contributions. A. Layden developed and applied the tuning methodology and code, accessed all meteorological and LSWT data, performed the data analysis and prepared the manuscript. S. MacCallum derived the ARC-Lake LSWT observations and provided technical support. C. Merchant initiated the ARC-Lake project and supervised the work in this study.

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Tables

ERA data components and description	*FLake* input
SSRD (shortwave solar downward radiation); 3 hourly SSRD, cumulative over 12 hour forecasts (W/m^{-2})	Mean daily SSRD W/m^{-2}
T2; 6 hourly air temperature at 2 metres (K)	Mean daily T2 ($^{\circ}C$)
D2; 6 hourly dewpoint at 2 metres (K),	Mean daily vapour pressure (hPa) $= P(z)*10^{(7.5(dewpoint / (237.7+dewpoint))}$ Where P(z) = P(sea level)*exp(-z/H). P(*z*)= pressure at height *z*, P(sea level)= sea level pressure (~1013 mb), z = height in metres, H= scale height (~7 km) http://www.gorhamschaffler.com/humidity_formulas.htm
U10 and V10; 6 hourly wind components at 10 meters (m/s)	Mean daily wind speed (m/s); $= \text{sqrt}(V10^2 + U10^2)$ U component represents eastward wind (west to east wind direction) V component represents northward wind (south to north wind direction)
TCC (total cloud cover); 6 hourly TTC	Mean daily TCC

Table 1 ECMWF Interim Re-analysis (ERA) data ~~component description~~components and *FLake* input format

Effective depth factors (Z_d)	Light extinction coefficient (κ_d)				albedo (α)	Snow & white ice Albedo	Melting snow & blue ice albedo
	κ_d	375nm	475nm	700nm			
Z_{d1}	$\kappa_{d\,1}$	0.038	0.018	0.56	$\alpha 1$	0.60	0.10
	$\kappa_{d\,2}$	0.052	0.025	0.57	$\alpha 2$	0.80	0.60
Z_{d2} (Z_{d1}* 0.75)	$\kappa_{d\,3}$	0.066	0.033	0.58	$\alpha 3$	0.80	0.40
Z_{d3} (Z_{d1}* 0.5)	$\kappa_{d\,4}$	0.122	0.062	0.61	$\alpha 4$	0.60	0.30
Z_{d4} (Z_{d1}* 1.5)	$\kappa_{d\,5}$	0.22	0.116	0.66			
	$\kappa_{d\,6}$	0.80	0.17	0.65			
Z_{d5} (Z_{d1}* 0.3)	$\kappa_{d\,7}$	1.10	0.29	0.71			
Z_{d6} (Z_{d1}* 2.5)	$\kappa_{d\,8}$	1.60	0.43	0.80			
Z_{d7} (Z_{d1}* 2.0)	$\kappa_{d\,9}$	2.10	0.71	0.92			
Z_{d8} (Z_{d1}* 4.0)	$\kappa_{d\,10}$	3.00	1.23	1.10			

Table 2 ~~Lake~~Effective depth~~,~~ factors (Z_d), light extinction coefficient values (κ_d) and snow and ice albedo ~~factor/~~ values (α) used in tuning study~~;~~. Eighty (80) possible combinations used for tuning of seasonally ice-covered lakes (~~plain text only)~~Z_{d1} : Z_{d4} x κ_{d1} : κ_{d5} x $\alpha 1$: $\alpha 4$) . The modified tuning for the 25 shallow seasonally ice-covered lakes utilised greater depth factors; Z_{d6} : Z_{d8} and 2 higher light extinction coefficient values, κ_{d6} and κ_{d7}. Sixty (60) possible combinations used for tuning of non-~~seasonally~~ ice covered lakes (~~plain and bold text; all 6 Z_d factors~~Z_{d1} : Z_{d6} x ~~all~~κ_{d1} : κ_{d10}) . The spectre for the 10 κ_d values~~)~~ are divided (in fractions of 0.18, 0.54, 0.28) into three wavelengths: 375, 475 and 700nm, respectively.

LSWT-regulating properties	Effect on metric	Metrics (mean differences between observed and modelled LSWTs)
κ (light extinction coefficient)	κ affects irradiance transmission of surface water, which is more notable in summer months.	JAS LSWT mean difference ($^{\circ}$C) $= (\bar{x}_i^{mod\_jas} - \bar{x}_i^{obs\_jas})$ $^{mod\_jas}$ = modelled JAS LSWT $^{obs\_jas}$ = observed JAS LSWT
d (depth)	*d* alters heat storage capacity affecting timing of the start of the cold phase (the day that the LSWT drops to below 1 $^{\circ}$C)	1 $^{\circ}$C cooling day mean difference (days)
α (snow and ice albedo)	α alters ice/snow reflectance affecting the end of the cold phase (the day that the LSWT increases to above 1 $^{\circ}$C)	1 $^{\circ}$C warming day mean difference (days)
d, α and κ	All LSWT-regulating properties contribute to the comparability of the modelled and observed LSWT	Daily MAD ($^{\circ}$C) $= \sum (\mathrm{abs}(x_i^{mod} - x_i^{obs})) / N$; ^{mod} = daily modelled LSWTs ^{obs} = daily observed LSWTs N = sample size

Table 3 Relationship between the Lake Surface Water Temperature (LSWT) regulating properties and ~~primary~~ metrics, showing the equations for determining the daily mean absolute difference (MAD) and the July, August, September (JAS) LSWT ~~bias~~

[mean difference]

Trial results for untuned model							
Seasonally ice-covered trial lakes (21 lakes)				Non-ice covered lakes (14 lakes)			
Metrics	u1	u2	u3	Metrics	u1	u2	u3
MAD (°C) (daily mean absolute difference)	3.07 ±2.25	2.66 ±1.93	2.02 ±1.30	MAD (°C)	3.55 ±3.20	3.11 ±2.77	2.17 ±1.93
Mean JAS (July August September) LSWT mean difference (°C)	3.71 ±3.51	3.07 ±3.41	1.87 ±2.93	mth_{max} (°C) (mean difference between observed and modelled LSWTs for the month of maximum observed LSWT)	1.92 ±5.05	1.39 ±5.06	-0.42 ±5.18
1 °C cooling day (the day the lake-mean LSWT drops to below 1 °C) mean difference (days)	12.0 ±39.6	7.9 ±33.3	1.0 ±30.5	mth_{min} (°C) (mean difference between observed and modelled LSWTs for the month of minimum observed LSWT)	3.71 ±4.33	3.08 ±4.16	1.47 ±3.87
1 °C warming day (the day the lake-mean LSWT rises to above 1 °C) mean difference (days)	- 27.1 ±29.7	- 23.6 ±22.7	- 20.3 ±18.4				

Table 4 The effect of wind speed ~~scalings~~scaling on untuned modelled LSWTs~~ of~~, presented as the ~~seasonally~~mean difference, between the modelled and ~~non-seasonally ice covered trial~~observed values, across lakes~~,~~ with the spread of differences ~~across lakes, 2σ.~~defined as 2σ, where wind speeds *u1* is unscaled, *u2* is factored by 1.2 and *u3* (U_{water} = 1.62+1.17U_{land}). Results are presented for seasonally ice-covered and non-ice covered trial lakes. Results highlight that *u3* is most applicable to seasonally ice-covered lakes but there is no one wind speed most suited for all lakes (While the ~~average bias~~mean difference is improved with *u3*, the spread of ~~biases~~the mean differences across lakes for mth_{min} and mth_{max} show little change).

Seasonally ice-covered lakes				Non-ice covered lakes			
metrics	Untuned (21 trial lakes)	Tuned (21 trial lakes)	Tuned (160 lakes)	Metrics	Untuned (14 trial lakes)	Tuned (14 trial lakes)	Tuned (84 lakes)
MAD (°C)	3.07 ±2.25	0.84 ±0.51	0.80 ±0.56	MAD (°C)	3.55 ±3.20	0.96 ±0.63	0.96 ±0.66
Mean JAS LSWT mean difference (°C)	3.71 ±3.51	-0.12 ±1.09	-0.06 ±1.15	mth_{max} (°C)	1.92 ±5.05	-0.44 ±1.52	-0.21 ±1.47
1 °C cooling day mean difference (days)	12.0 ±39.6	-1.6 ±12.8	-1.08 ± 8.5	mth_{min} (°C)	3.71 ±4.33	-0.03 ±1.48	-0.08 ±1.47
1 °C warming day mean difference (days)	- 27.1 ±29.7	-0.2 ±10.7	0.3 ±12.3				

Table 5 Summary of the untuned and tuned metrics for the trial ~~seasonally and non-seasonally ice covered~~ lakes and the tuned metrics for all ~~seasonally and non-seasonally ice covered lakes showing the spread of differences~~lakes (metrics are explained in Table 4). The results, presented for seasonally ice-covered and non-ice covered lakes in each instance, show the mean between the modelled and observed values, across lakes~~,~~ with the spread of differences defined as 2σ.

Tuning metrics	135 lakes	25 lakes (modified tuning)	All lakes (160)	Trial lakes
MAD (°C)	0.74± 0.48	1.11± 0.56	0.80± 0.56	0.84± 0.51
Mean JAS mean difference (°C)	-0.01± 1.11	- 0.34±1.22	-0.06± 1.15	-0.12± 1.09
1 °C cooling day mean difference (days)	-1.0± 8.8	-1.3± 6.9	-1.08± 8.5	-1.6 ± 12.8
1 °C warming day mean difference (days)	0.5± 12.6	- 0.5± 10.2	0.3± 12.3	-0.2± 10.7

Table 6 ~~Metric~~Comparison of metric results for seasonally ice-covered lakes ~~(~~: 135 lakes tuned using the ~~original tuned set-up, table~~initial tuned setup for seasonally ice-covered lakes (Table 2 ~~and~~), 25 lakes tuned with the ~~modified~~modified set-up~~), compared with the results for the~~ (Table 2), all lakes, and trial lakes~~, showing the~~. The spread of differences across lakes~~,~~ is defined as 2σ. The metrics are explained in Table 4.

Tuned metrics	Tuned results for 160 seasonally ice-covered lakes			
	Saline (37 lakes)	Freshwater (123 lakes)	Altitude >3200 m a.s.l. (14 lakes)	Altitude < 2000 m a.s.l. (146 lakes)
MAD (°C)	0.90± 0.69	0.76± 0.50	0.61± 0.24	0.81± 0.57
Mean JAS mean difference (°C)	-0.23± 1.14	-0.01± 1.14	0.06± 1.14	-0.07± 1.15
1 °C cooling day mean difference (days)	-1.3± 9.7	-1.0± 8.3	-3.1± 10.8	-0.9± 8.2
1 °C warming day Mean difference (days)	0.0± 13.1	0.4± 12.0	0.9± 13.6	0.3± 12.1

Table 7 Comparison of tuned model results for saline, freshwater, high and low altitude seasonally ice-covered lakes, with the spread of differences across lakes, 2σ. The metrics are explained in Table 4.

Tuned metrics	Tuned results for 84 non-ice covered lakes			
	Saline (26 lakes)	Freshwater (58 lakes)	Altitude > 1500 m a.s.l. (10 lakes)	Altitude < 1500 m a.s.l. (74 lakes)
MAD (°C)	1.06 ±0.67	0.91 ±0.64	1.03 ±0.82	0.95 ±0.64
mth_{max} (°C)	-0.31 ±1.90	-0.16 ±1.24	-0.40 ±2.12	-0.18 ±1.37
mth_{min} (°C)	-0.25 ±1.74	-0.01 ±1.33	-0.14 ±1.30	-0.07 ±1.50

Table 8 Comparison of tuned metric results for saline, freshwater and high and low altitude non-~~seasonally~~ ice covered lakes, with the spread of differences across lakes, 2σ. The metrics are explained in Table 4.

Non-ice covered lakes	All lakes (84)	Temperate lakes >20° N/S (44 lakes)	Tropical lakes < 20° N/S (40 lakes)
var$_{max}$ (K^2) the inter-annual variance in the mean LSWT observations for the month of maximum LSWT	0.40	0.65	0.12
inter$_{max}$ (R^2_{adj}) The fraction of the observed variances (*var*$_{max}$) accounted for in the tuned model	0.29± 0.63	0.49± 0.58	0.07± 0.31
var$_{min}$ (K^2) the inter-annual variance in the mean LSWT for the month of minimum LSWT	0.43	0.69	0.15
inter$_{min}$ (R^2_{adj}) The fraction of the observed variances (*var*$_{min}$) accounted for in the tuned model	0.25± 0.49	0.37± 0.49	0.13± 0.37
Seasonally ice-covered lakes	All lakes (160)	Altitude >3200 m a.s.l. (14 lakes)	Altitude < 2000 m a.s.l. (146 lakes)
var$_{jas}$ (K^2) the inter-annual variance in the mean JAS LSWT	0.70	0.19	0.75
Inter$_{jas}$ (R^2_{adj}) The fraction of the observed variances (*var*$_{jas}$) accounted for in the tuned model	0.50± 0.62	0.21± 0.46	0.52± 0.59

Table 9 The fraction (R^2_{adj}) of observed inter-annual ~~variability~~variance detected in the model~~, for the maximum~~. Maximum and minimum LSWT is used for non-~~seasonally~~ ice covered lakes (*inter*$_{max}$ and *inter*$_{min}$~~)~~)), while July, August and ~~for the~~ September (JAS) LSWT is used for seasonally ice-covered lakes, (*inter*$_{jas}$~~), highlighting~~). This table highlights that where the observed inter-annual ~~variability~~variance is low, the proportion of ~~variability~~variance detected in the model is also low (high altitude seasonally ice-covered lakes and tropical lakes~~)~~)).

Tuned metrics	135 lakes			25 lakes (modified tuning set-up)		
	2011 Untuned	1996 Tuned (ATSR2)	2010 Tuned (Advanced ATSR)	2011 Untuned	1996 Tuned (ATSR2)	2010 Tuned (Advanced ATSR)
MAD (°C)	0.86±0.68	0.89±0.74	0.87±0.71	1.59±1.04	1.33±0.79	1.66±0.95
Mean JAS mean difference (°C)	0.18±1.50	-0.33±1.79	0.28±1.44	0.12±1.71	0.17±1.19	0.28±1.81
1 °C cooling day mean difference (days)	11.1±23.8	5.1±25.6	8.5±21.4	10.9±18.7	-3.0±41.9	11.7±31.3
1 °C warming day mean difference (days)	7.4±19.7	12.1±19.7	6.5±19.8	9.33±21.6	13.2±18.2	1.0±32.54

Table 10 Results of independent evaluation of the tuning process for seasonally ice-covered lakes~~ with the~~. The spread of differences across lakes~~,~~ is defined as 2σ~~, showing~~. These results illustrate that the metrics (explained in Table 4) from the untuned year (2011) compare well with metrics from 1996 (the ~~first~~first full year of data from Along-Track Scanning Radiometers 2 (ATSR2) and 2010 (the last year of tuned data from ~~AATSR)~~

Advanced ATSR. For the untuned year (2011), for each lake, the model is forced with the effective lake depth (*Zd*), snow and ice albedo (α) and light extinction coefficient (*κd*) values determined during the tuning process, shown in the supplement.

Tuned Metrics	2011 Untuned	1996 Tuned (ATSR2)	2010 Tuned (Advanced ATSR)
MAD (°C)	1.07±0.91	0.98±0.82	0.97±0.81
mth_{max} (°C)	-0.23±2.40	-0.32±1.86	-0.31±2.20
mth_{min} (°C)	-0.02±2.04	-0.23±1.73	+0.11±2.15

Table 11 Results of the independent evaluation of the tuning process for non-~~seasonally~~ ice covered lakes~~ 3 with the~~. The spread of differences across lakes~~,~~ is defined as 2σ~~, showing~~. Metrics (explained in Table 4) for the untuned year (2011) are compared with those from the ~~first~~first full year of data from Along-Track Scanning Radiometers 2 (ATSR2) (1996) and the last year of tuned data from ~~AATSR (2010)~~Advanced ATSR (2010). For the untuned year (2011), for each lake, the model is forced with the effective lake depth (Z_d), snow and ice albedo (α) and light extinction coefficient (κ_d) values determined during the tuning process, shown in the supplement.

Figures

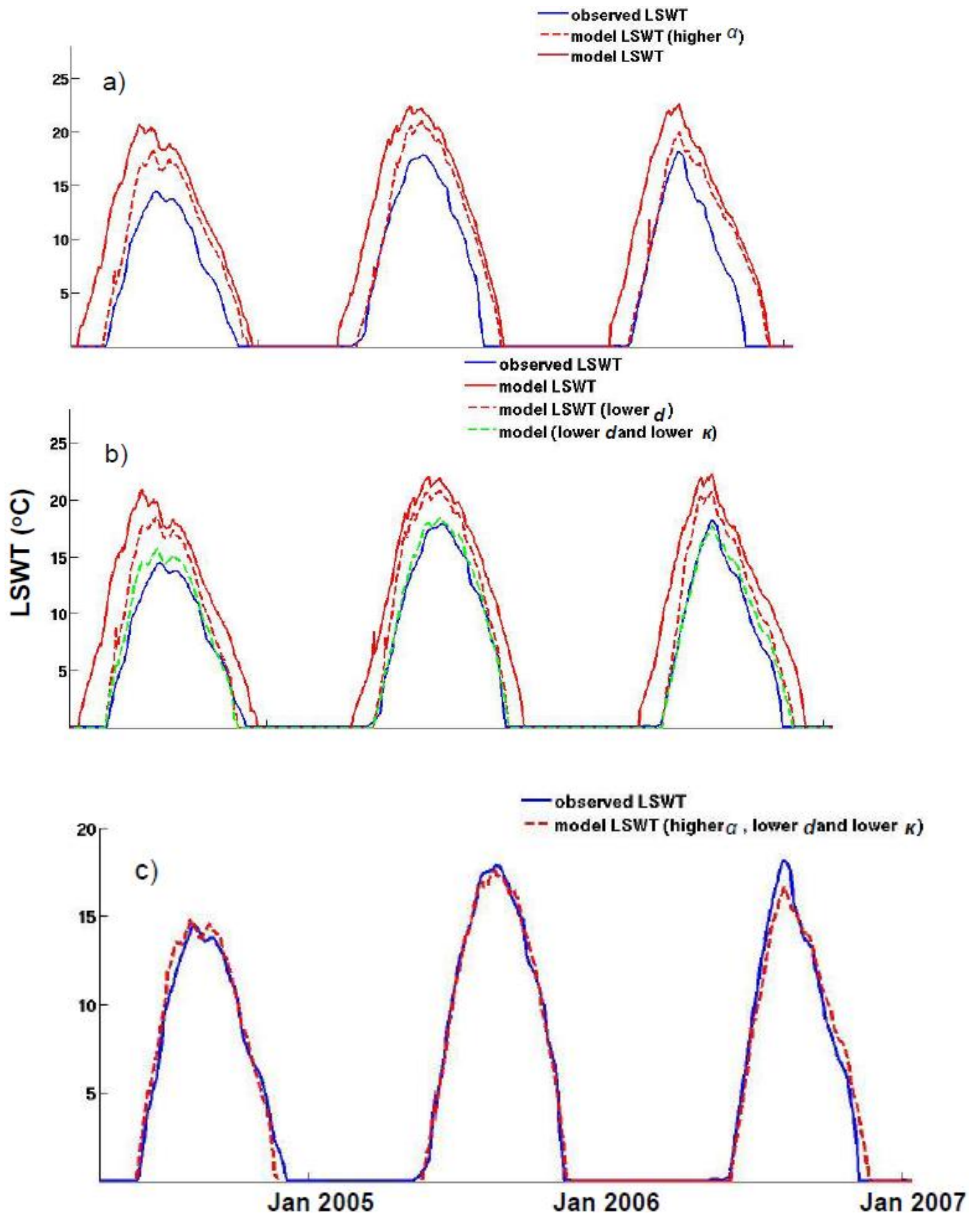
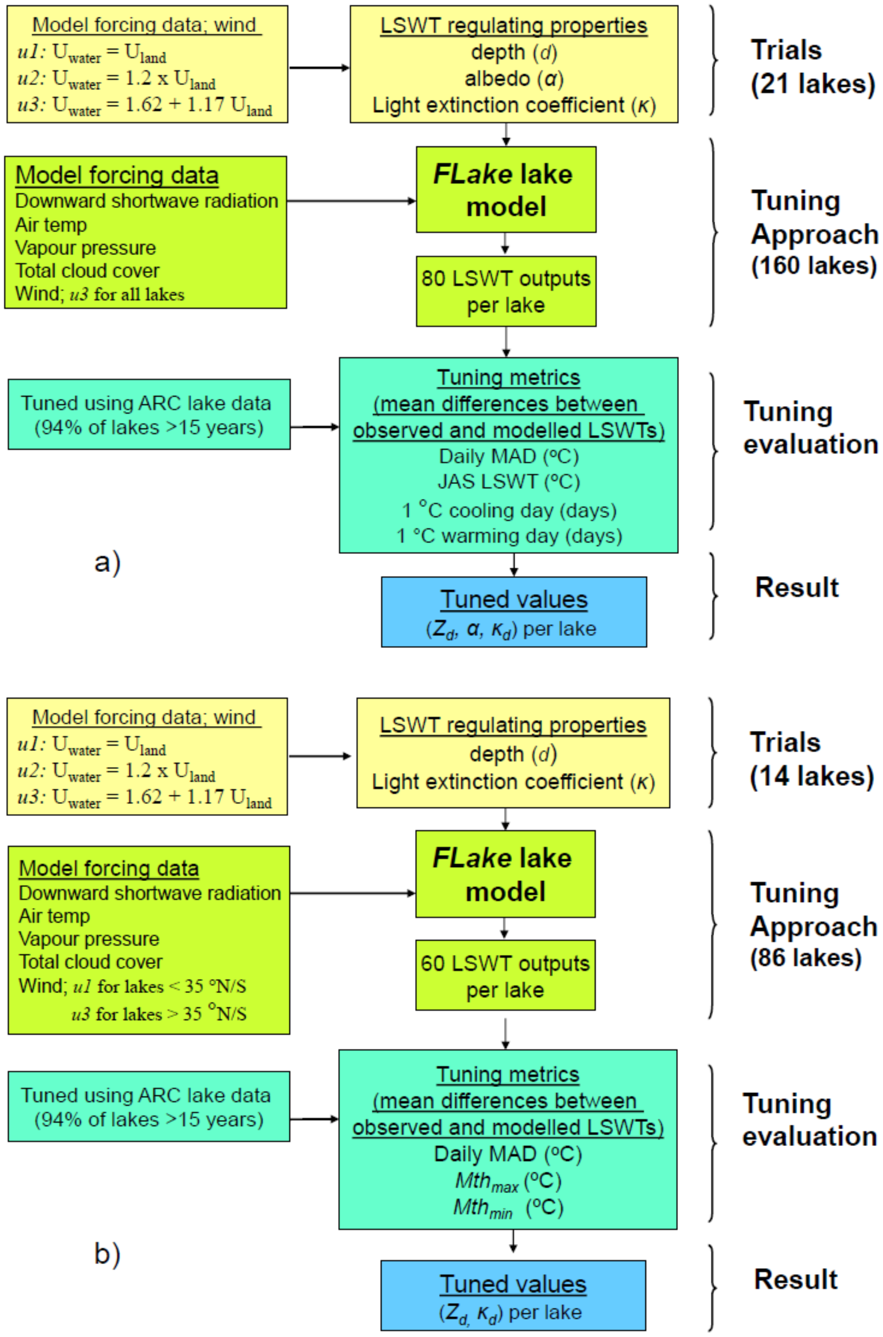


Figure 1 Preliminary modelled runs for Lake Athabasca, Canada (59° N 110° W), showing that adjustments to lake depth (d~~, α~~), snow and ice albedo (α) and light extinction coefficient (κ) can greatly improve the modelled lake surface water temperatures (LSWTs) compared to the default/ recommended d, α and κ values; a) shows that a higher α causes a later ~~and more timely~~ ice-off date, comparing well with the observed (ARC-Lake) ice-off date, b) shows that a lower d causes an earlier ~~and more timely~~ ice-on date and a lower κ value (greater transparency) reduces the maximum LSWT and c) shows that the combined

effect of the adjusted d, α and κ produce LSWTs that are highly comparable to the observed ARC-Lake LSWTs.



~~**Figure 2**~~

Figure 2 Study approach overview (trials, tuning, evaluation and results) for a) seasonally ice-covered lakes and b) non-ice covered lakes. For the trials, wind speed scaling, *u1*, *u2* (recommended for lakes with fetch < 16 km and *u3* recommended for open ocean water) is assessed on the untuned model, tuning is then trialed with a range of factors for d and values for α and κ using the selected wind speed scaling. The tuning approach produces modelled LSWTs for all possible combination of d, α and κ, 80 modelled runs for seasonally ice-covered lakes and 60 for non-ice covered lakes. For the evaluation, the tuning metrics (normalized and equally weighted) are the basis for selection of the optimal (tuned) LSWT model for each lake.

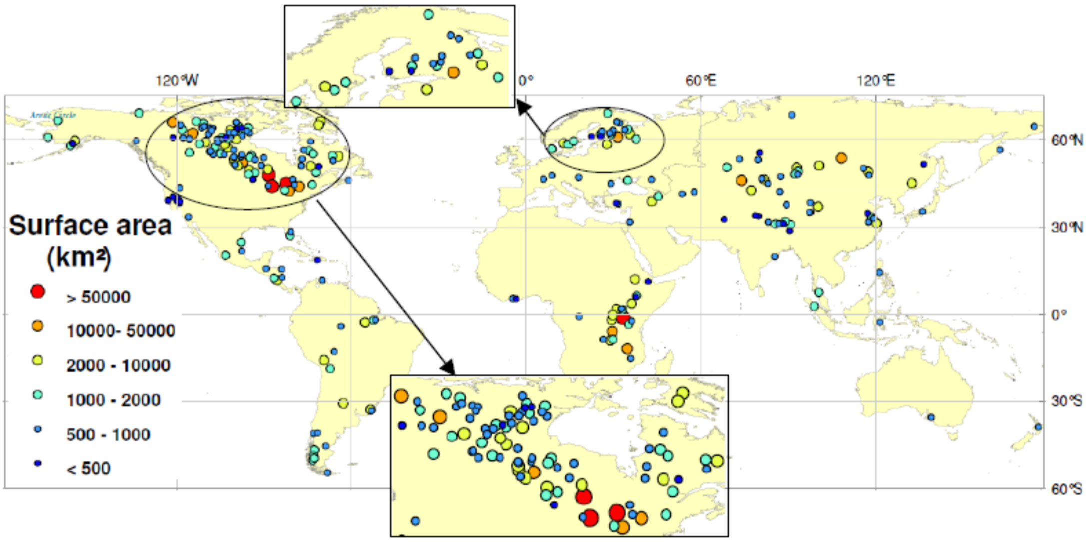


Figure 3 Location of 246 observed lakes colour coded by surface area (obtained using polygon area in Global Lakes and Wetlands Database (GLWD) showing zoomed inset of North America and Northern Europe.

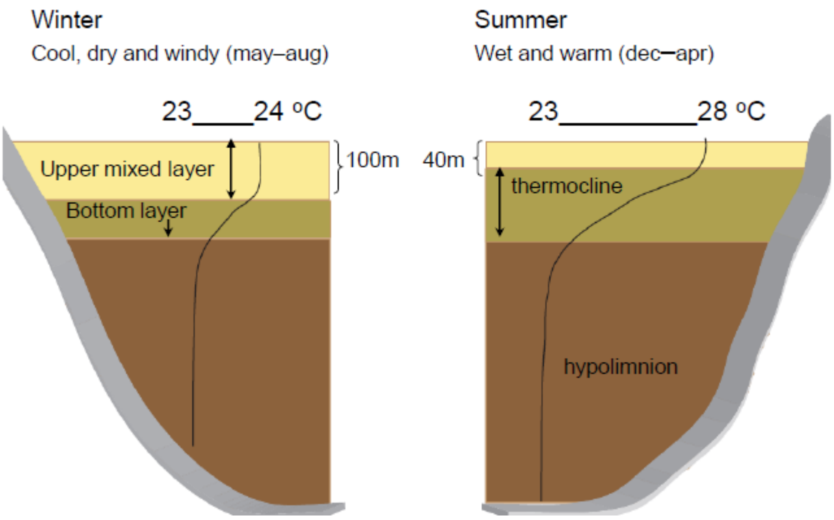


Figure ~~3~~4 Summer and winter mixing and temperature profile of Lake Malawi~~;~~, Africa (12° S 35° E), illustrated using data from the ILEC world lake database (http://wldb.ilec.or.jp/); showing ~~a~~the summer and winter lake water surface temperature (LSWT), mixed layer depth ~~of 40-100 m.~~, thermocline temperature gradient and the hypolimnion. *FLake* ~~predicts~~is a two-layer model, capable of predicting the LSWT, the depth and ~~depth~~temperature of the 'upper mixed layer' and the temperature of the 'bottom layer'

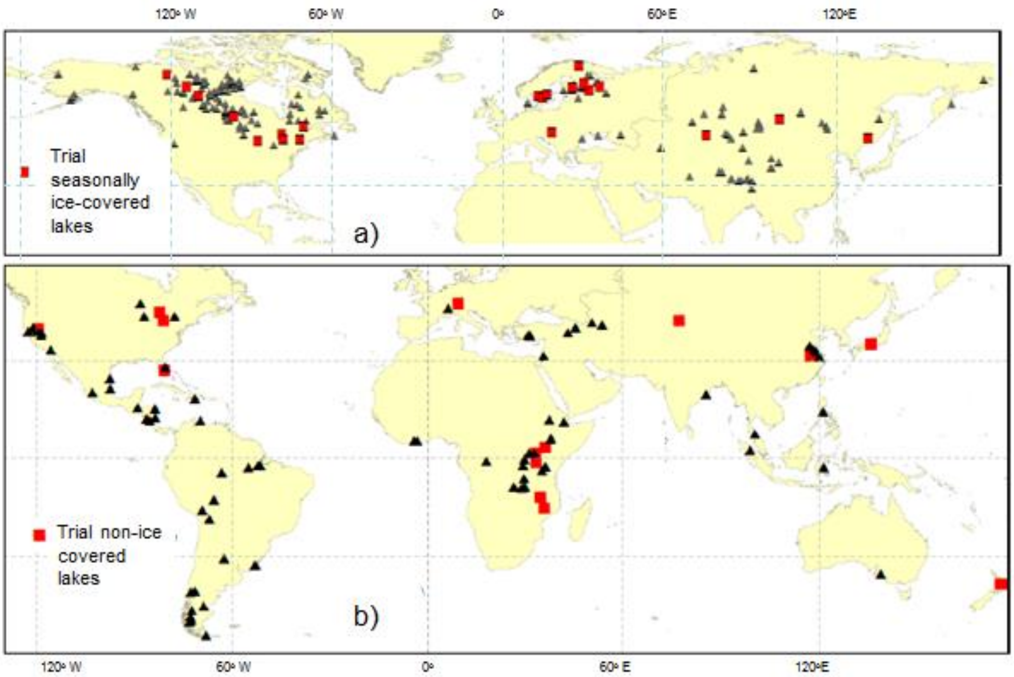


Figure 45 Location of lakes, with red square showing the trial lakes a) 160 seasonally ice-covered lakes, including 21 trial lakes and b) 86 non-~~seasonally~~ ice covered lakes including 14 trial lakes

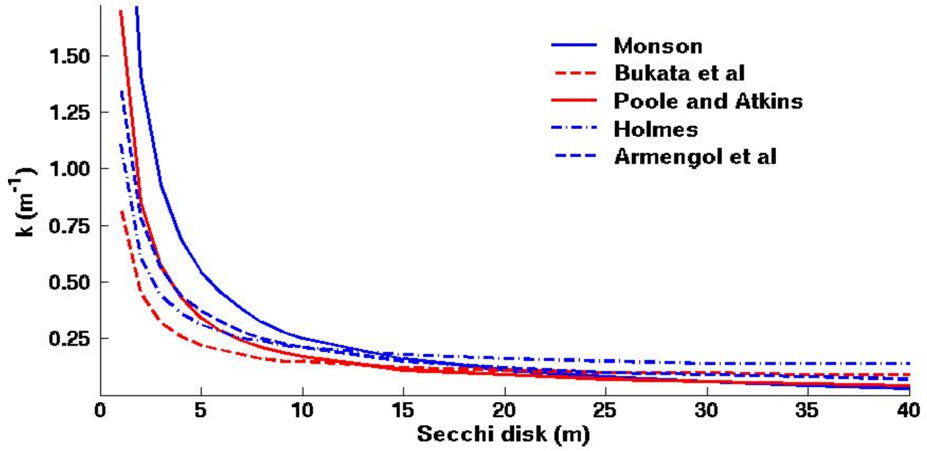


Figure ~~5~~6 A comparison of 5 methods relating light extinction coefficients to Secchi disk depths, showing that all method compare reasonably well at Secchi disk depths > 10 m

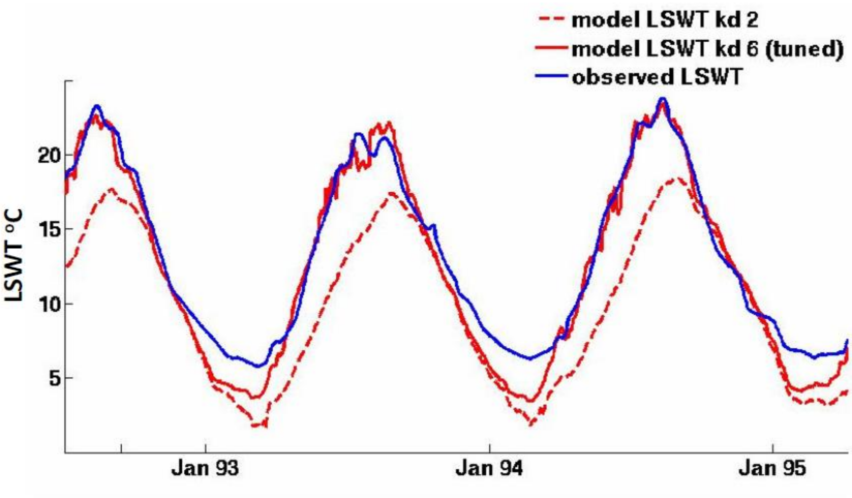


Figure ~~6~~ 7 Lake surface water temperatures (LSWTs) for Lake Geneva, Europe (46° N 6° E), modelled with two different κ_d values (κ_{d2} κ_{d6}; table 2) shows the substantially stronger effect of κ_d on the maximum LSWT than the minimum LSWT.

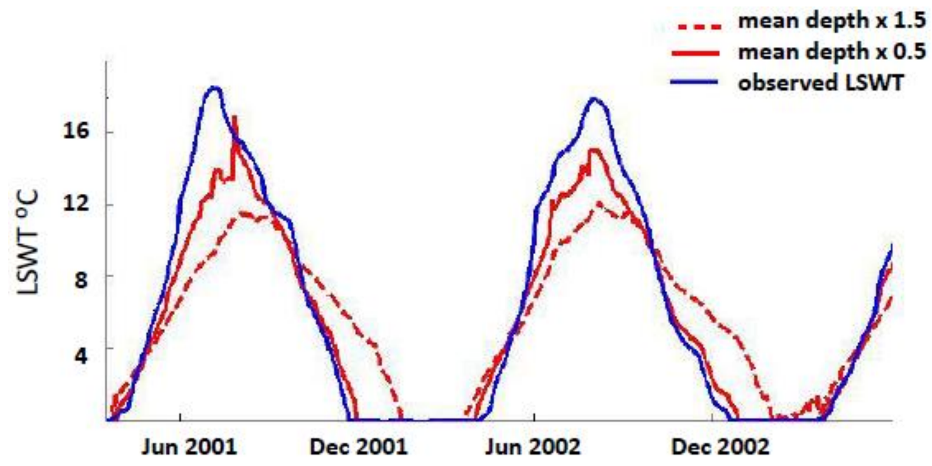


Figure ~~7~~8 Effect of depth on the lake surface water temperature (LSWT) for Lake Ladoga, Russia (61° N 31° E), (mean depth 52 m), showing that when modelled with a greater depth, the lake cools later and the maximum LSWT is lower

~~**Figure 8** Tuning approach overview for a) seasonally ice covered lakes and b) non-seasonally ice covered lakes~~

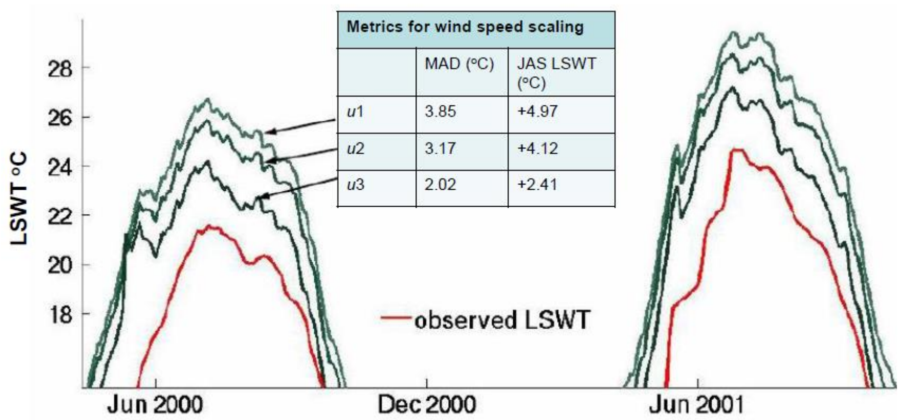


Figure 9 Effect of wind speed scalings on the modelled lake surface water temperature (LSWT) for Lake Simcoe, Canada, 44° N 79° W (depth 25 m), showing that the ~~*u3*~~ greatest wind speed scaling ~~halves~~, *u3* ($U_{water} = 1.62+1.17U_{land}$), in place of the unscaled wind speed, *u1*, reduces the daily ~~MAD and JAS~~mean absolute difference and July, August September LSWT ~~bias~~

mean difference by ~50%. Modelled with untuned LSWT properties: mean lake depth (Z_{d1}), default snow and ice albedo ($\alpha 1$) and light extinction coefficient derived from Secchi disk depth data (κ_{sd})

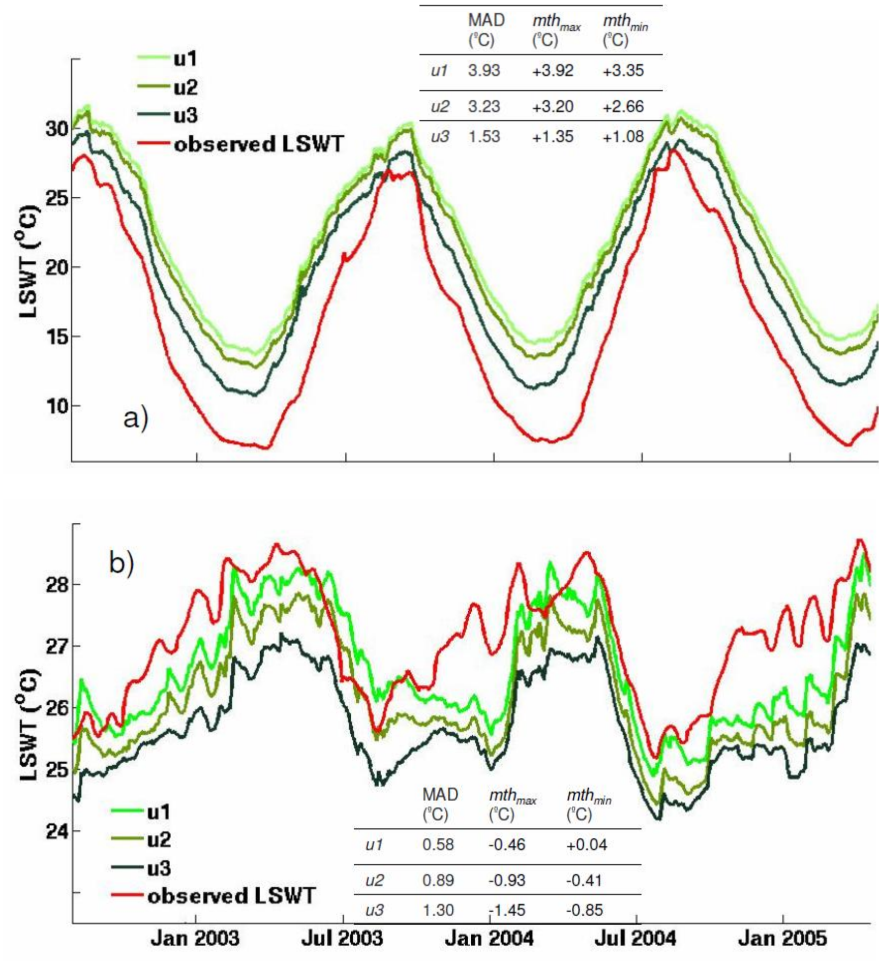


Figure 10 Effect of wind speed scaling on lake surface water temperatures (LSWT) for a temperate non-~~seasonally~~ ice covered lake a) Lake Biwa, Japan (~~35.6~~ 36° N 136° E) and for a tropical non-~~seasonally~~ ice covered lake b) Lake Turkana, Africa (~~3.5~~ 4° N 36° E) showing that the modelled LSWT for the temperate lake is better represented using *u3* ($U_{water} = 1.62+1.17U_{land}$), and the modelled LSWT for the tropical lake is better represented using *u1* (unscaled wind speed). mth_{min} (and mth_{max}) is the difference between the observed and modelled LSWTs for the month where the minimum (and maximum) LSWT is observed

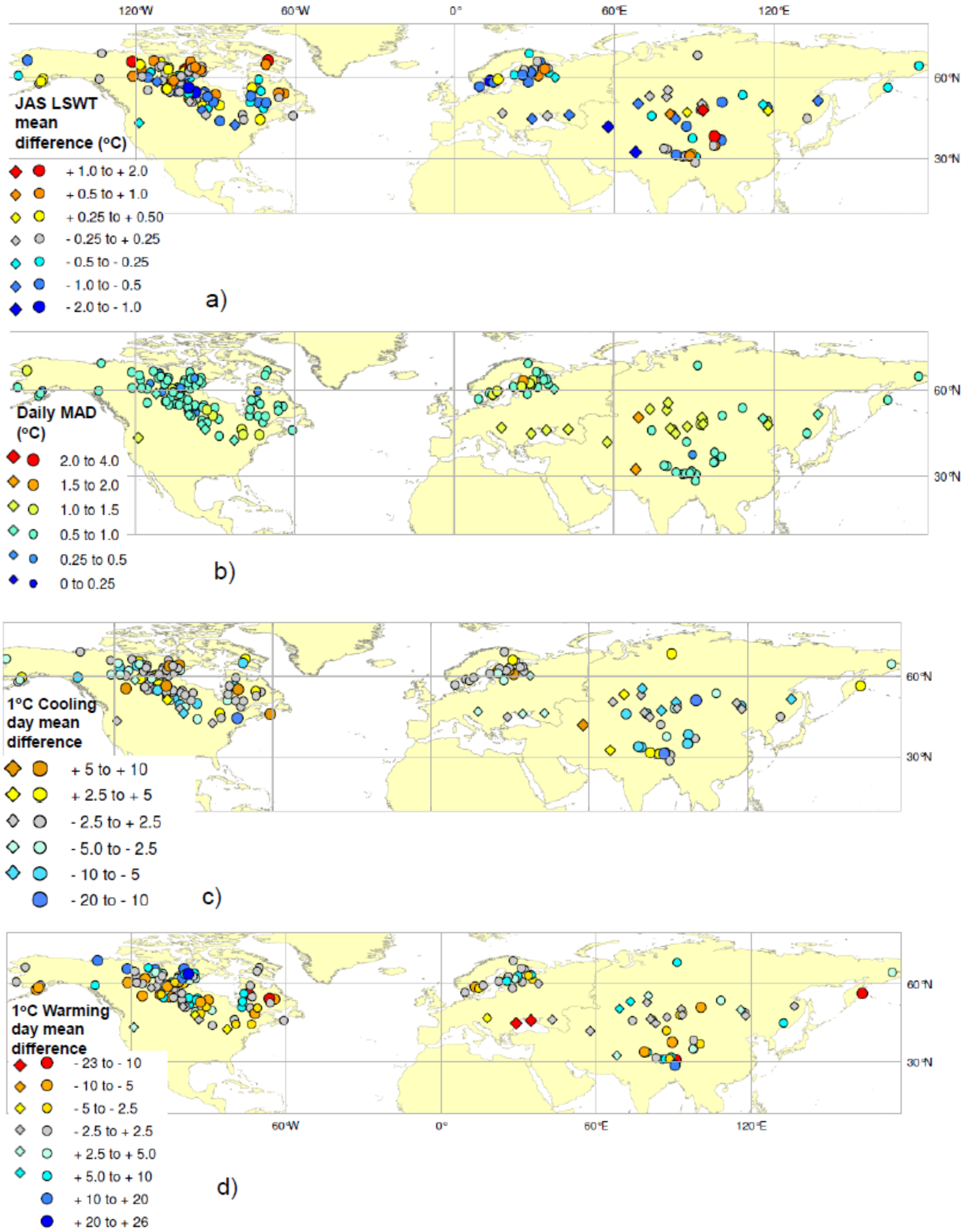


Figure 11 Tuning metric ~~results~~mean differences between modelled and observed LSWTs for all 160 lakes with seasonal ice-cover. The results for the 25 lakes tuned with modified tuning approach are marked by diamond symbols a) July August September (JAS ~~bias~~) LSWT mean difference, b) Daily mean absolute difference (MAD ~~bias,~~), c) 1 °C cooling day ~~bias~~mean difference and d) 1 °C warming day ~~bias~~

mean difference

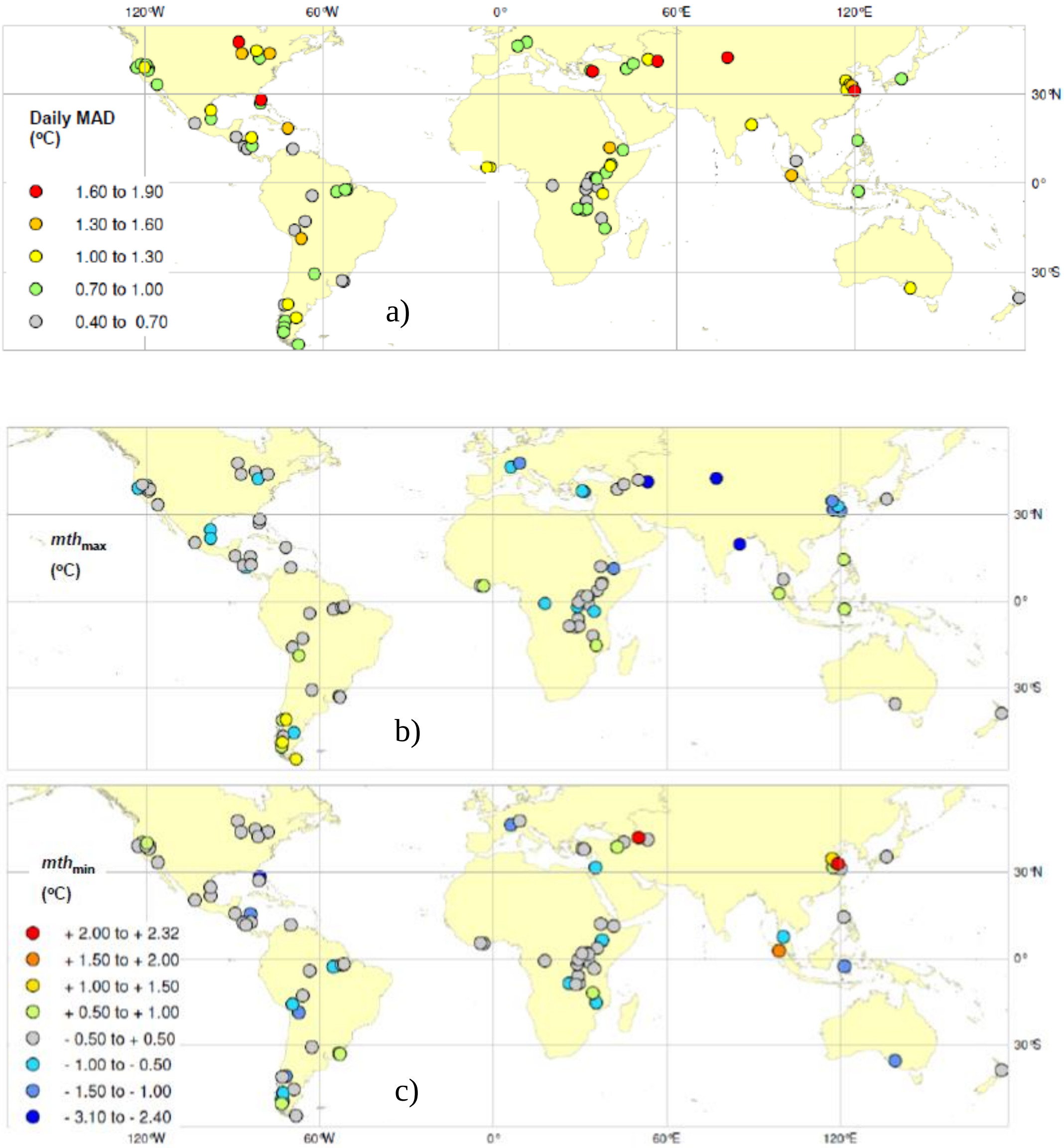


Figure 12 Tuning metric results for the 84 ~~lakes with~~ non-~~seasonally~~ ice ~~cover~~covered lakes a) Daily mean absolute difference (MAD) between observed and modelled LSWTs, b) mth_{max} and c) mth_{min}. mth_{min} (and mth_{max}) is the difference between the observed and modelled LSWTs for the month where the minimum (and maximum) LSWT is observed

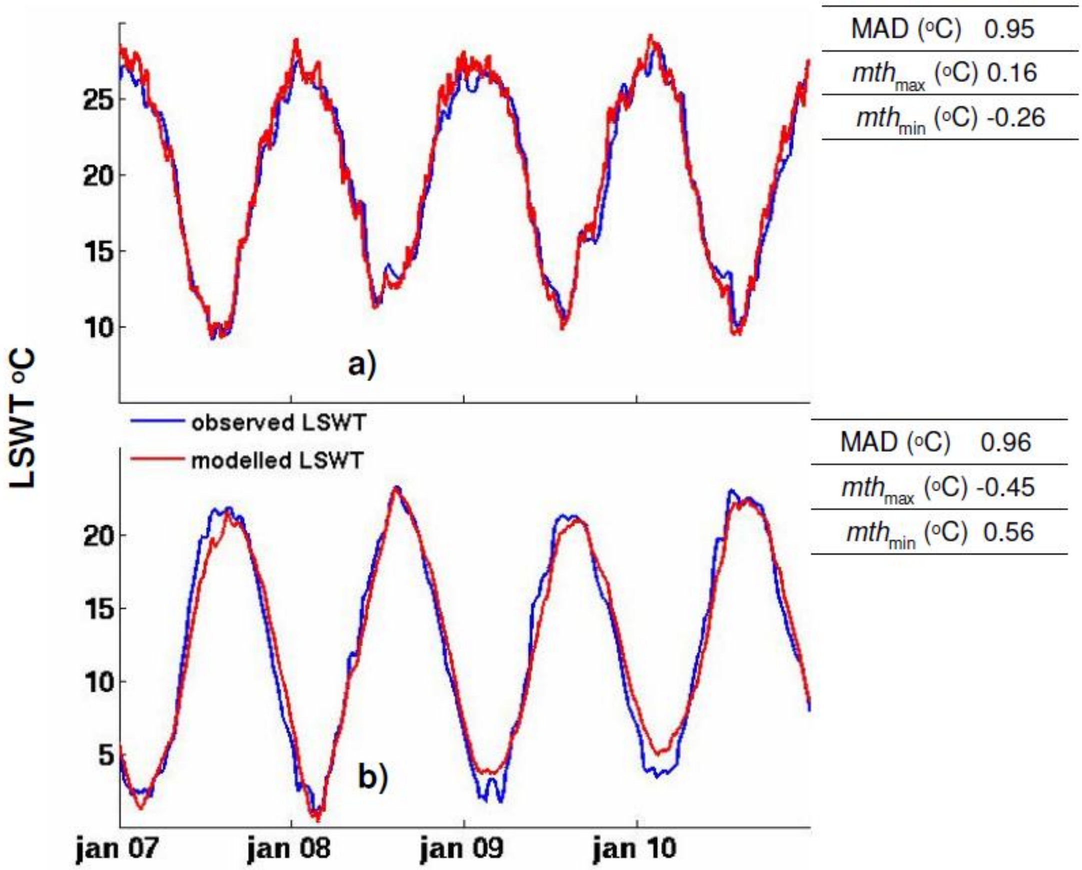


Figure 13 Observed LSWT versus tuned model LSWT for saline and high altitude lakes a) Lake Chiquita, Argentina (31° S 63° W, salinity 145 g~~/l~~ L^{-1}) b) Lake Van, Turkey (~~38~~° 39° N 43° E, 1638 m a.s.l., salinity 22 g~~/l)~~

L^{-1}).

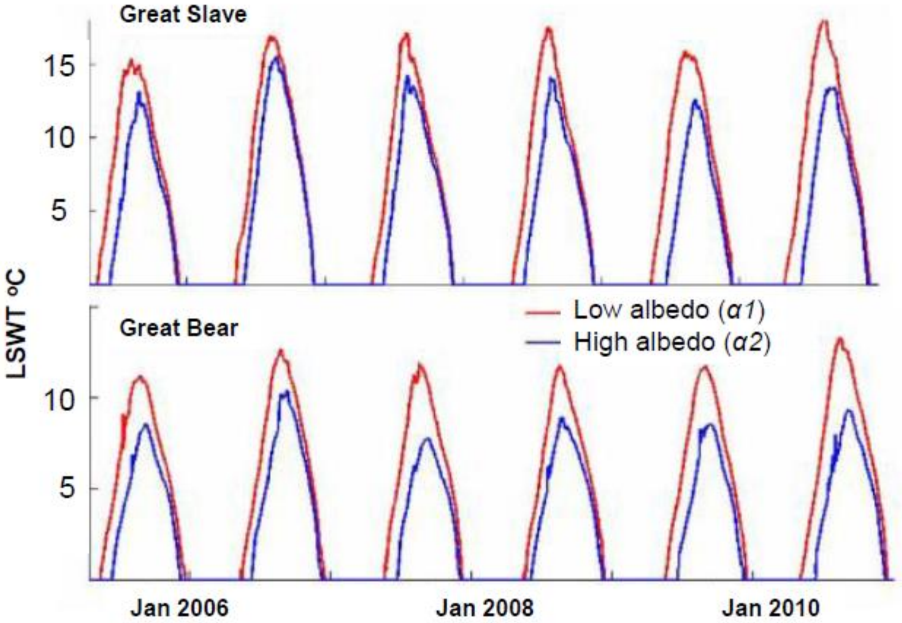


Figure 14 Lake surface water temperatures (LSWTs) for Great Bear (66° N 121° W) and Great Slave (62° N 114° W)modelled with low snow and ice albedo (default albedo~~)~~ ~~and high albedo (~~, $\alpha 1$: snow and white ice = 0.60 and melting snow and blue ice = 0.10) and high albedo ($\alpha 2$: snow and white ice = 0.80 and melting snow and blue ice = 0.60) demonstrating that the higher snow and ice albedo delays the 1 °C warming day, causing a lower ~~JAS~~July August September LSWT

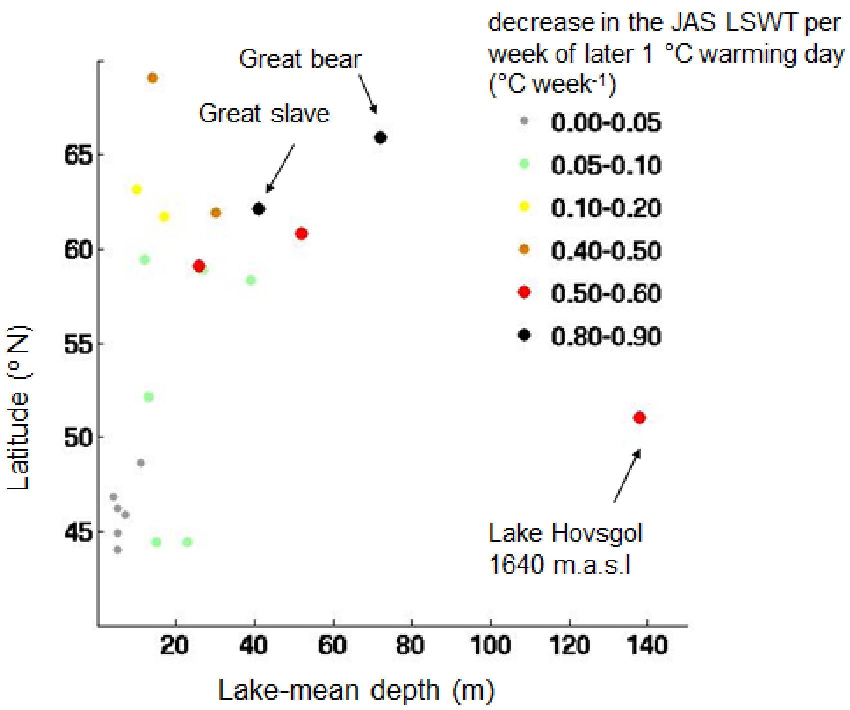


Figure 15 The ~~JAS LSWT decrease (shown as °C decrease per week of later 1 °C warming day) caused by a higher snow and ice albedo for the 21 trial lakes shown with respect to lake depth and~~ relationship between latitude~~. This figure shows~~ and lake-mean depth of the 21 trial seasonally ice-covered lakes and the decrease in the July August September (JAS) lake surface water temperature (LSWT) caused by the later 1 °C warming day (as a result of using a high albedo, $\alpha 2$: snow and white ice = 0.80 and melting snow and blue ice = 0.60 in place of the default albedo $\alpha 1$: snow and white ice = 0.60 and melting snow and blue ice = 0.10). The changes in the JAS LSWT, presented as the decrease in the JAS LSWT, per week of later 1 °C warming day, °C week^{-1}, are categorised by coloured circles. This figure indicates that high latitude and deep lakes show ~~largest JAS LSWT~~a larger decrease ~~with~~ in the JAS LSWT per week of later 1 °C warming day, signifying that the ~~LSWT~~LSWTs of ~~high latitude and deep~~these lakes are more responsive to changes in the 1 °C warming day~~.~~

, than low latitude and shallow lakes.

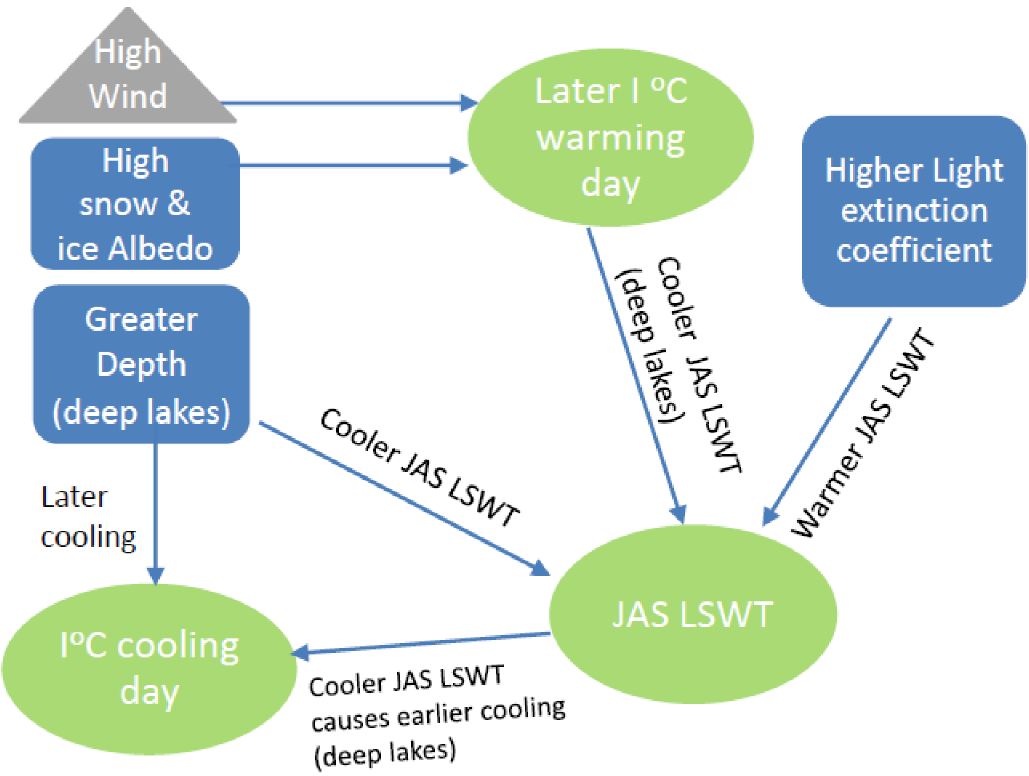


Figure 16 Schematic linking the interactions between the lake surface water temperature (LSWT) regulating parameters ~~(blue~~: lake depth (*d*), snow and ice albedo (*α*) and light extinction coefficient (*κ*), shown in squares~~)~~ and wind (shown in triangle) with the LSWT ~~phases (green~~metrics: 1 °C cooling day, 1 °C warming days and July August September (JAS) LSWT (shown in circles~~)~~

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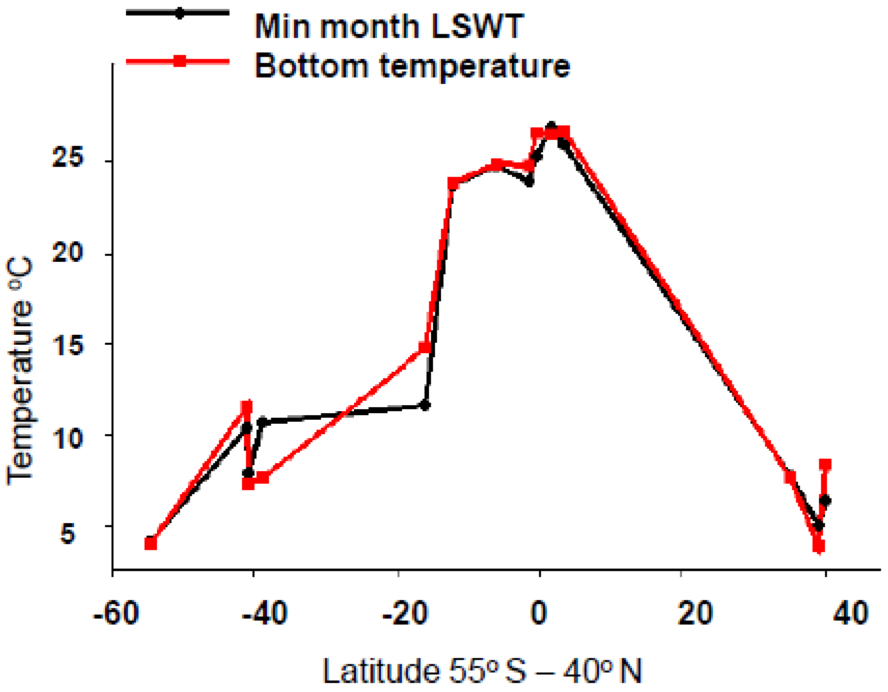

Figure 17 ~~Lake~~ Comparison of lake-bottom ~~temperature~~temperatures during the stratification ~~and climatological monthly minimum LSWT of 14 deep (>25 m) non-seasonally ice covered lakes from 55° S to 40° N, showing the modelled equilibrium result (lake bottom temperatures~~ period, obtained from *FLake* ~~lake~~ model~~,~~ run using perpetual hydrological year, 2005/~~2006) compared with observed~~ 06 (Kirillin et al., 2011) and the monthly minimum climatology ~~(1992-2011) LSWTs~~ lake surface water temperature (LSWT) observations from ARC-Lake, for 14 deep (> 25 m) non-ice covered lakes (55 °S to 40 °N). The monthly minimum observed LSWTs have a ~1:1 relationship with the lake-bottom temperatures during the stratification period.

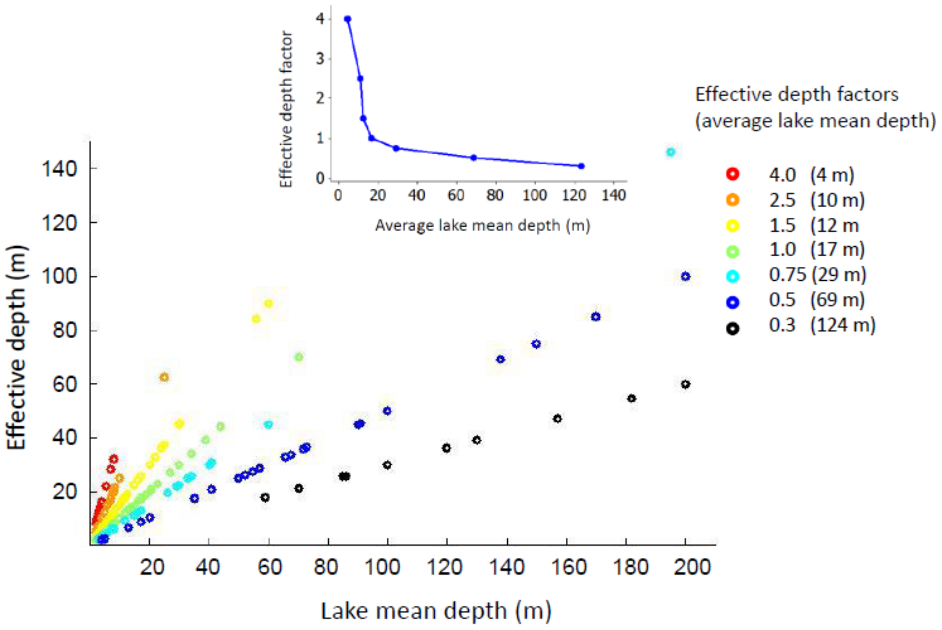

Figure 18 The lake mean depth ~~versus~~vs. the modelled effective depth for 244 tuned lakes~~, colour coded by~~. Colour coding illustrates the effective depth factors~~ and the~~. The average lake depth for each effective depth factor used in the tuning process is also given (insert~~), demonstrating~~). This figure demonstrates that deeper lakes are tuned to a ~~lower~~shallower effective depth and shallower lakes to a ~~greater~~deeper effective depth.