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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 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 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. 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. For all other trial lakes (14 non-ice covered lakes), the improvement is from 3.55 ± 3.20 °C to 0.96 ± 0.63 °C. The post tuning results for the 35 trial lakes (21 seasonally ice-covered lakes and 14 non-ice covered lakes) are highly representative of the post-tuning results of the 244 lakes.

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. Lake depth alone explains 0.35 (p = 0.003) of the variance. 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.

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 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).

Reliable modelling of LSWTs can enrich our understanding of the highly variable dynamic nature of lakes. In this paper, a 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. *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 mean differences between the modelled and observed LSWTs (overestimation of the open water LSWTs and underestimation of the ice cover period). Despite these 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 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 $\leq 1\ ^{\circ}C$ between the modelled (tuned) and observed LSWTs, across all lakes. A mean daily MAD of $\leq 1\ ^{\circ}C$ 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.

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 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. The modelled LSWT is further improved by lowering the κ value (greater transparency). The greater transmission of surface heat to the lower layers 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 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 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-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-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. In order to capture the critical features of both seasonally ice-covered and non-ice covered lakes, the mean difference in the features between the observed and modelled LSWTs differ 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

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). 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.

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. 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. 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 (Mironov, 2008). The lake conditions of the homogeneous ‘upper mixed layer’ (epilimnion) and the ‘bottom layer’ as represented in Fig. 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 mean differences between the model and observed LSWTs are greatly 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*. Other lake-specific properties adjusted for this study are: c_relax_C, fetch, latitude and the starting conditions.

c_relax_C: a dimensionless constant used in the relaxation 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.

$$\text{fetch} = 39.9\ \text{km} + 0.00781\ \text{area km} \quad (1)$$

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: 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 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.

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).

2.3 Tuning method

A suitable range of factors/values for d, α and κ is determined through the model trials (carried out on 21 seasonally ice-covered lakes and 14 non-ice covered lakes, Fig. 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 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. 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. 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 becomes increasingly large. Bukata et al. (1998) showed that the formula Eq. (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;

$$\kappa_{sd} = (0.757/ S) + 0.07 m^{-1} \qquad (2)$$

where S = Secchi disk depth (m).

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 suitable for large lakes outside this Secchi disk depth range (less than 2 m and greater than 10 m), 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).

$$\kappa_{sd} = 1.7/ S \qquad (3)$$

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 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 spectre 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. 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 non-ice covered lakes. 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’.

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

2.3.4 Tuning of snow and ice albedo

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 *α1* in this study. During the preliminary trials, a higher albedo (than *α1*) 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 (*α2* : *α4*), 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.

2.3.5 Wind speed scaling

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

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

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, α and 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 60 possible combinations for non-ice covered lakes.

2.4 Tuning metrics

The tuning metrics are the 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 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. The effect that the tuned lake depth (effective depth) has on the 1 °C cooling day (the day the lake-mean LSWT drops below 1 °C; an indicator of ice-on) is demonstrated in Fig. 8. The 1 °C warming day (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-ice covered lakes

The metrics for non-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 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 ice-covered lakes and non-ice covered lakes

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 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. The calculations to quantify var_{jas} and $inter_{jas}$ are shown in Eqs. (5) and (6).

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

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

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;

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

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”.
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 Trial results for wind speed scaling

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 lowering 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. 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 mean difference in the length of the average cold phase (when compared to the observed cold phase) by ~ 50% (from 39 to 21 days) and reduces the JAS LSWT mean difference by ~ 50%, from 3.71 to 1.87 °C, Table 4. On 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-ice covered trial lakes, 5 of the 7 lakes at latitudes > 35° N/S show best results with *u3,* as demonstrated for 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 Lake Turkana, located at 3.5° N, Fig. 10b. Of the scalings applied, there is no optimal wind speed scaling for all non-ice covered lakes. This may be attributable to the highly variable range of latitudes, LSWTs and mixing regimes of non-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. 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-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 ice-covered lakes and non-ice covered lakes, is reduced from 3.07 ± 2.25 and 3.55 ± 3.20 °C for the untuned model 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 the model default albedo (seasonally ice-covered lakes only).

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 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 of below 1 °C was achieved (0.80 ± 0.56 °C, Table 5).

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.

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.

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). 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 these lakes require a greater modelled depth to increase the heat capacity - postponing the 1 ^{o}C cooling day - and lower transparency values (higher κ_d), causing less heat to be retained in the surface and lowering the JAS LSWT. Consequently, the modified tuning set-up, discussed below, was applied to these 25 lakes.

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). 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-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.

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.

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. 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. 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).

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 a negative modelled mean difference of 4.8 °C for the month of minimum LSWT. 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.

4.2 Tuning of saline and high altitude lakes

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) indicate that *FLake* is successful for tuning both saline and high altitude lakes, as well as freshwater and low altitude lakes. 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-ice covered lakes).

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.

The majority of the high altitude lakes are also saline; 7 of the 10 non-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. 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. 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 results show that the modelled LSWTs capture less of the true (observed) inter-annual 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 represented in the model, than lakes with greater observed LSWT variance and the annual range. This would also indicate that lakes in the Southern 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-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 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-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 variance have a greater portion of the variance detected in the model. For high altitude seasonally ice-covered temperate lakes, the fraction of the observed JAS LSWT inter-annual 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, $p < 0.0005$. Furthermore, the annual range of monthly LSWTs for non-ice covered lakes, explain 0.38 and 0.36 ($p < 0.0005$) 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 variance. This supports the findings that tropical and high altitude lakes are less well represented in the model.

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).

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. For the 25 shallow lakes tuned with the modified 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. 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 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 is more predictable for deeper lakes, as illustrated in Fig. 16, than for shallow lakes.

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-ice covered lakes, although the mean MAD and dispersion of errors is slightly higher for the untuned year, 2011, Table 11, 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) is demonstrated, for deep high latitude or very deep seasonally ice-covered lakes. Using the default snow and ice albedo (*α1*, Table 2), the modelled 1 °C warming day of the 21 trial lakes occur, on average, 20 days too early.

A higher albedo (*α2*, Table 2) delays the 1 ºC warming day by 27 $\pm$ 12.6 days and decreases the mean JAS LSWT mean difference by ~50%, to 0.98 $\pm$ 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. The LSWTs for Great Bear and Great Slave lakes modelled with α2 (high) and α1 (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, °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 the 1 °C cooling day 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, 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 a deep lake from reaching its maximum heat storage capacity. At higher latitudes, the LSWT warming period for northern hemispheric lakes 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.

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 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).

As the snow cover module with *FLake* is not operational in this version of the model; 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.

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-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.

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-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).

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.

5.3 Wind speed scaling for low latitude lakes

The trials showed that while non-ice covered lakes at latitudes < 35 °N/S required no wind speed scaling (*u*1), the largest wind speed scaling (*u*3) improved LSWTs for non-ice covered lakes at latitudes > 35 °N/S and all seasonally ice-covered lakes, as outlined in Sect. 3.

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 (0.352×10^{-3}kg/m^{-3}) than for lakes at latitudes above 35 °N/S (1.183×10^{-3}kg/m^{-3}). This is due to the smaller annual temperature range of the lower latitude lakes.

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. 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 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 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 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 shallower effective depth and shallower lakes to a deeper effective depth. Figure 18 shows the relationship between the 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 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 deeper effective depth may compensate for not having considered the 'heat flux from sediments' scheme in the model. Retention of heat in the sediments of a lake has the same effect as deepening the lake, causing an increase the heat storage capacity.

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 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} 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. 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. A comparison of the two model runs 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*.

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, $\alpha 1$, (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).

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 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. 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 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 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 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*; $U_{\text{water}} = 1.62 + 1.17U_{\text{land}}$), is most appropriate for lakes at higher latitudes > 35° N/S. 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.

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 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 ERA data covering a longer time span (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 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.

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

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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’, 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-ice covered lakes in August; Southern Hemisphere 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’.

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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 (^{o}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); $= sqrt (V10^2 + U10^2)$ 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 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 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.

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 (°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 °C)	1 °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 °C)	1 °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 (°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 metrics, showing the equations for determining the daily mean absolute difference (MAD) and the July, August, September (JAS) LSWT 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 scaling 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).

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 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.

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 Comparison of metric results for seasonally ice-covered lakes: 135 lakes tuned using the initial tuned setup for seasonally ice-covered lakes (Table 2), 25 lakes tuned with the modified set-up (Table 2), all lakes, and trial lakes. 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 $\pm$0.67	0.91 $\pm$0.64	1.03 $\pm$0.82	0.95 $\pm$0.64
mth_{max} (°C)	-0.31 $\pm$1.90	-0.16 $\pm$1.24	-0.40 $\pm$2.12	-0.18 $\pm$1.37
mth_{min} (°C)	-0.25 $\pm$1.74	-0.01 $\pm$1.33	-0.14 $\pm$1.30	-0.07 $\pm$1.50

Table 8 Comparison of tuned metric results for saline, freshwater and high and low altitude non-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 variance detected in the model. Maximum and minimum LSWT is used for non-ice covered lakes (*inter*$_{max}$ and *inter*$_{min}$), while July, August and September (JAS) LSWT is used for seasonally ice-covered lakes, (*inter*$_{jas}$). 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).

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. 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.

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-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 (κ_d) values determined during the tuning process, shown in the supplement.

Figures

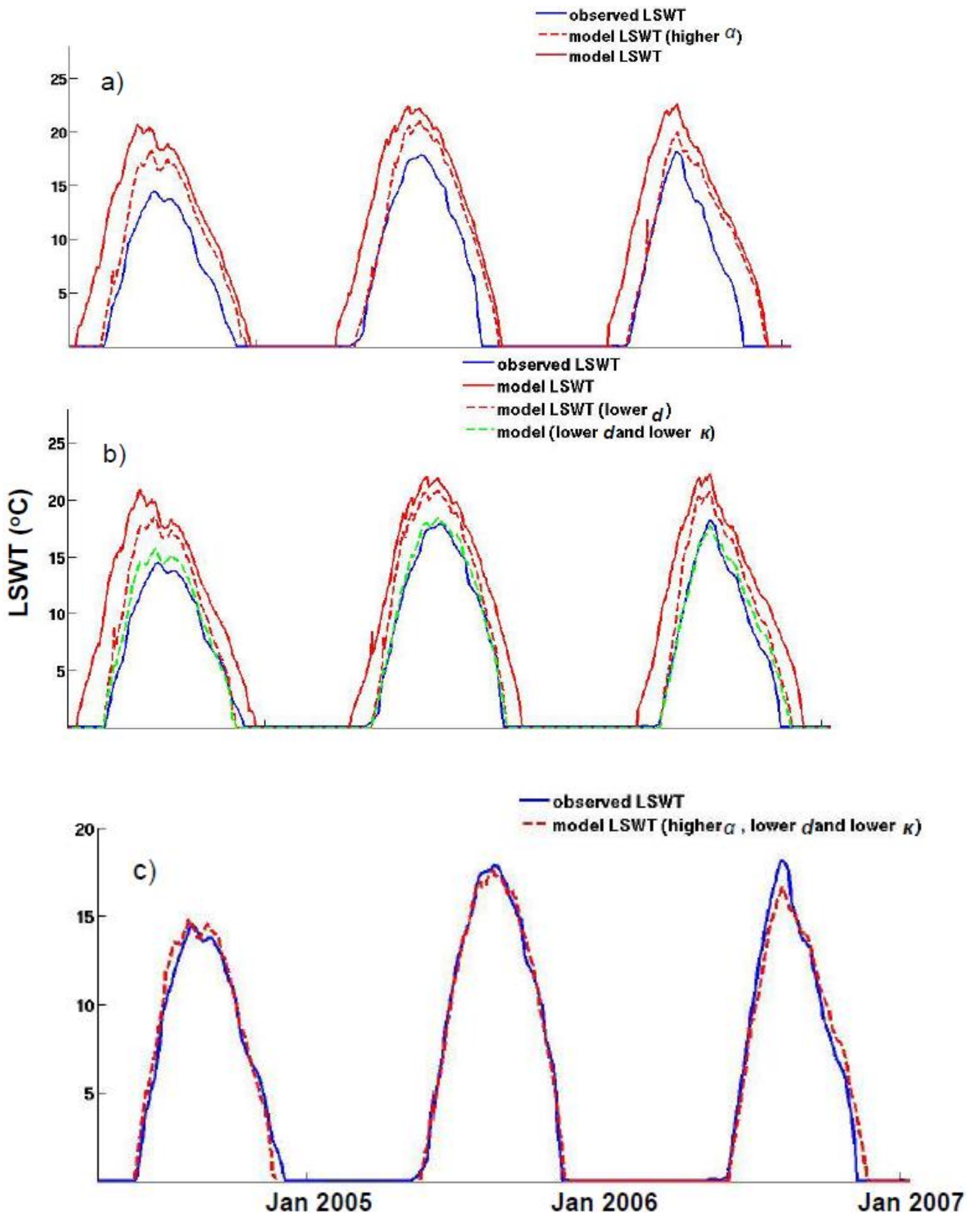

Figure 1 Preliminary modelled runs for Lake Athabasca, Canada (59° N 110° W), showing that adjustments to lake depth (*d*), snow and ice albedo (*α*) and light extinction coefficient (*κ*) can greatly improve the modelled lake surface water temperatures (LSWTs) compared to the default/ recommended *d*,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

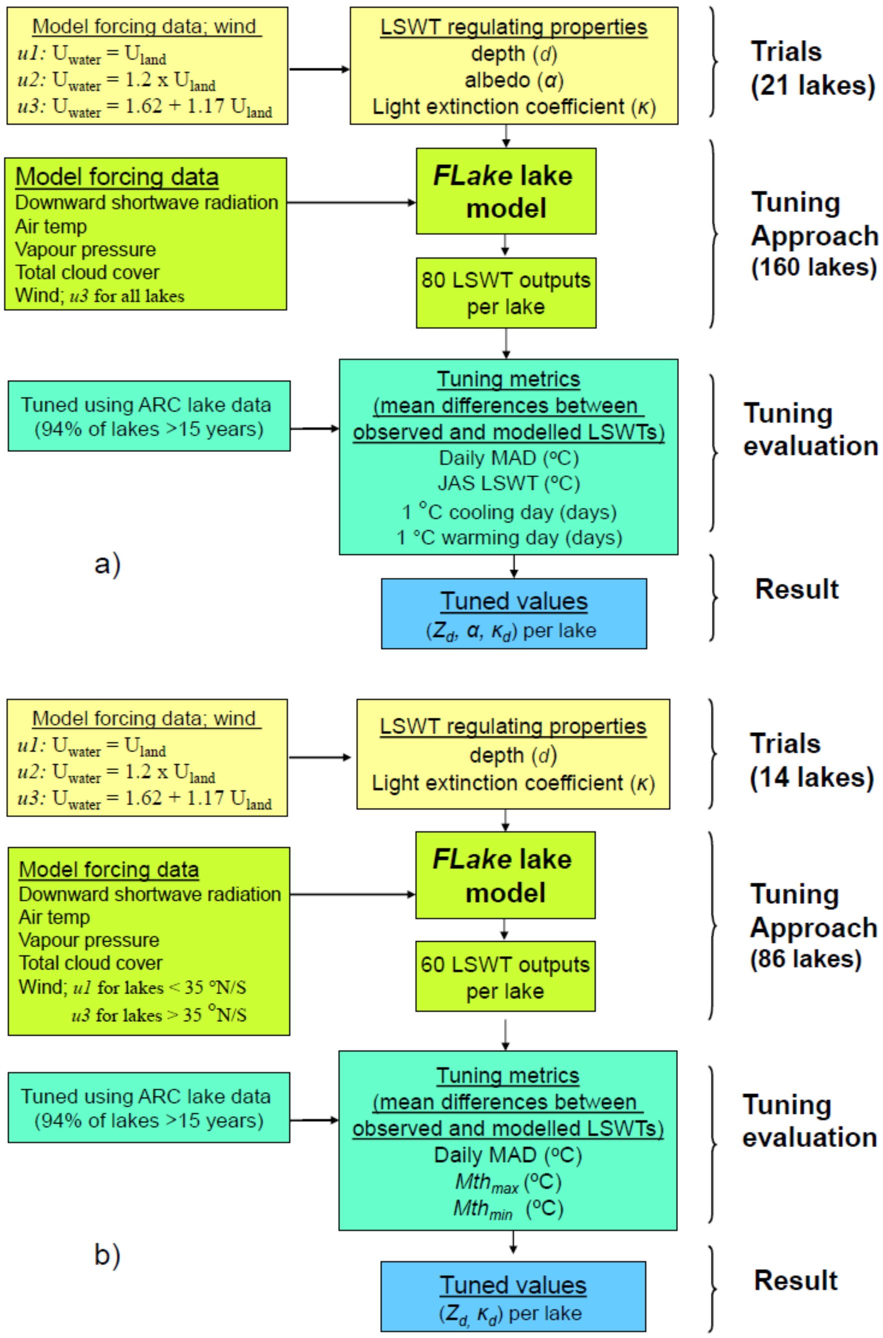

Figure 2 Study approach overview (trials, tuning, evaluation and results) for a) seasonally ice-covered lakes and b) non-ice covered lakes. For the trials, wind speed scaling, *u1*, *u2* (recommended for lakes with fetch < 16 km and *u3* (recommended for open ocean water) is assessed on the untuned model, 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.

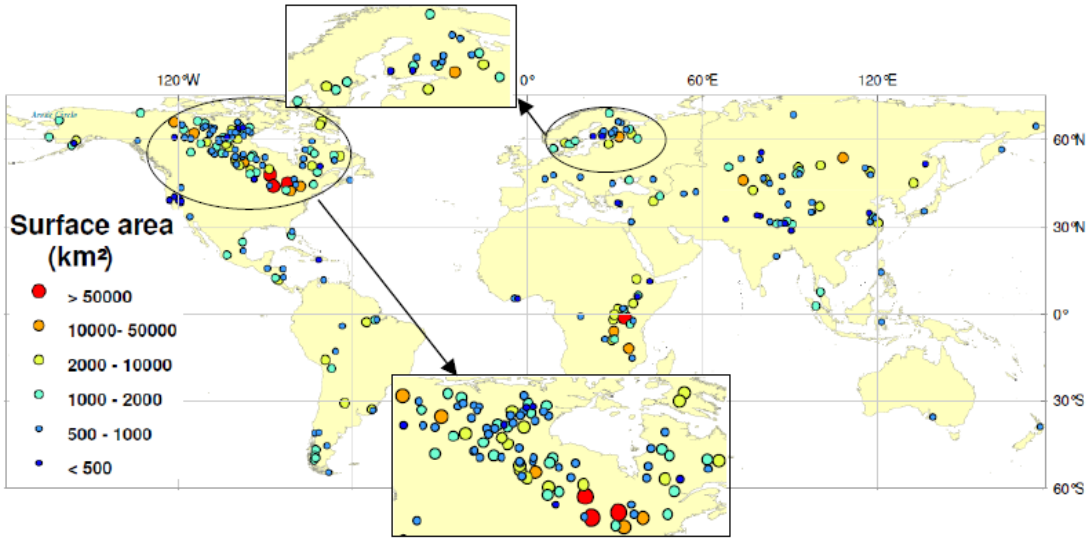

Figure 3 Location of 246 observed lakes colour coded by surface area (obtained using polygon area in Global Lakes and Wetlands Database (GLWD) showing zoomed inset of North America and Northern Europe.

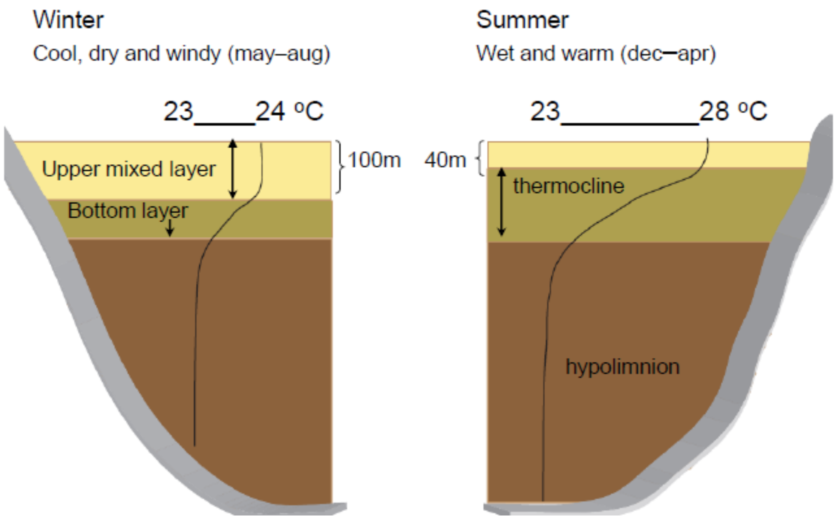

Figure 4 Summer and winter mixing and temperature profile of Lake Malawi, Africa (12° S 35° E), illustrated using data from the ILEC world lake database (http://wldb.ilec.or.jp/); showing the summer and winter lake water surface temperature (LSWT), mixed layer depth, thermocline temperature gradient 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'

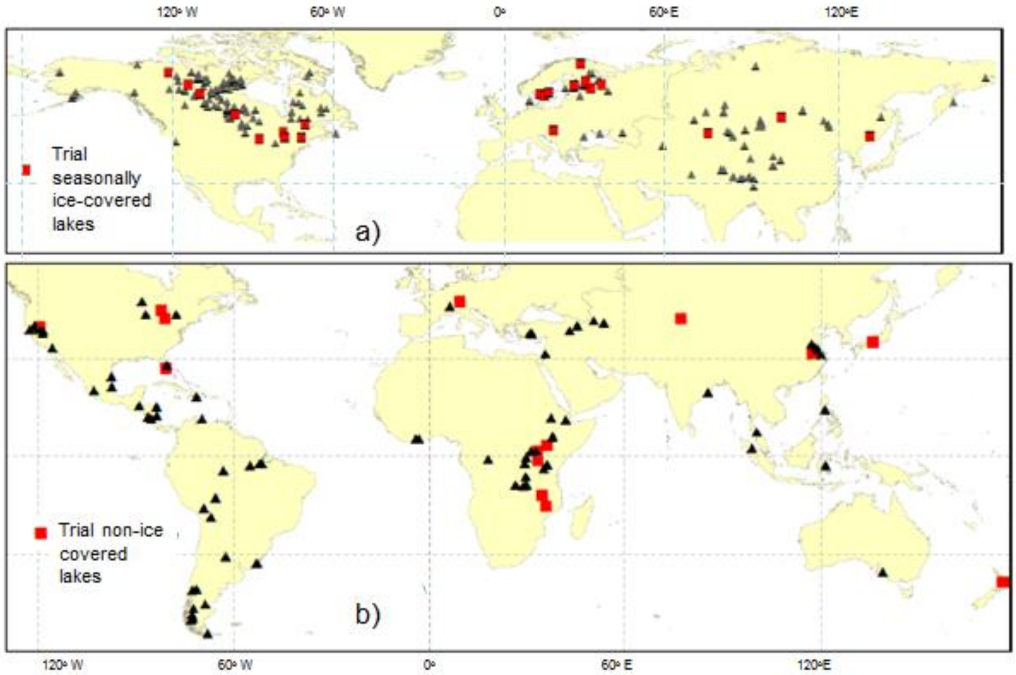

Figure 5 Location of lakes, with red square showing the trial lakes a) 160 seasonally ice-covered lakes, including 21 trial lakes and b) 86 non-ice covered lakes including 14 trial lakes

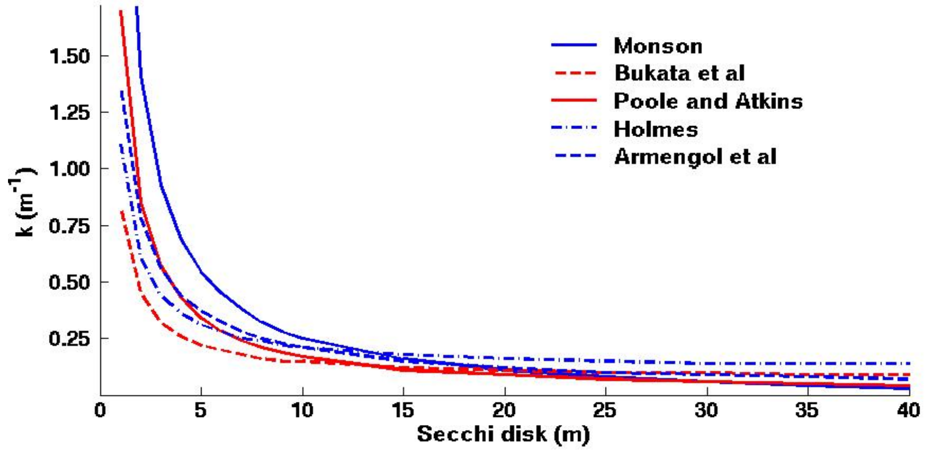

Figure 6 A comparison of 5 methods relating light extinction coefficients to Secchi disk depths, showing that all method compare reasonably well at Secchi disk depths > 10 m

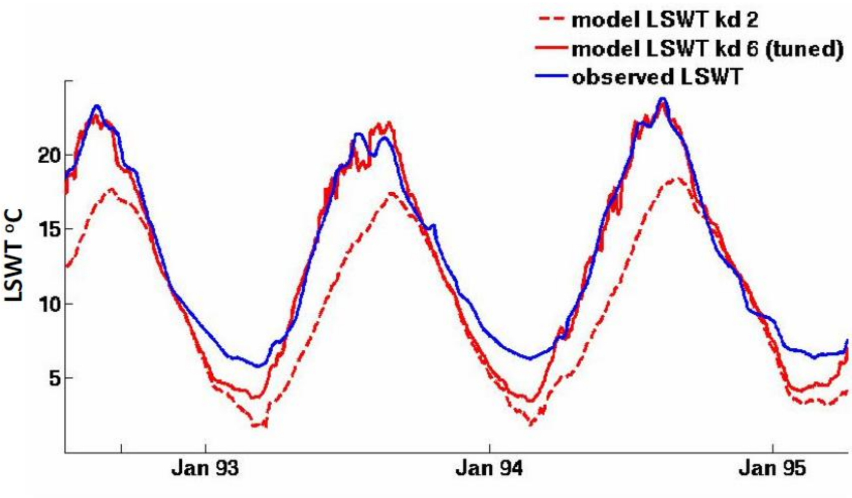

Figure 7 Lake surface water temperatures (LSWTs) for Lake Geneva, Europe (46° N 6° E), modelled with two different κ_d values (κ_{d2} $\kappa_{d6;}$ table 2) shows the substantially stronger effect of κ_d on the maximum LSWT than the minimum LSWT.

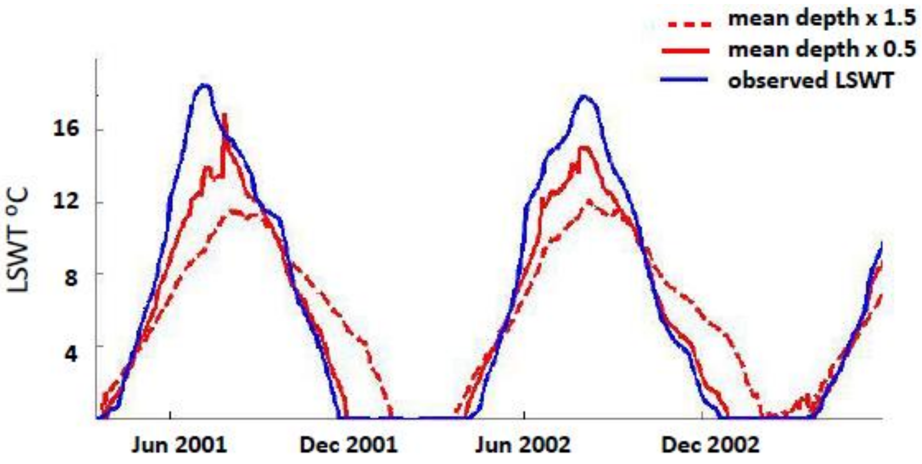

Figure 8 Effect of depth on the lake surface water temperature (LSWT) for Lake Ladoga, Russia (61° N 31° E), (mean depth 52 m), showing that when modelled with a greater depth, the lake cools later and the maximum LSWT is lower

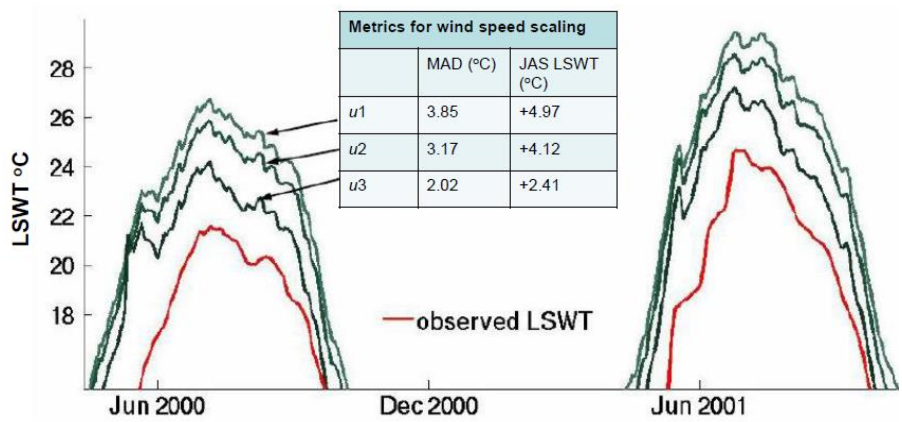

Figure 9 Effect of wind speed scalings on the modelled lake surface water temperature (LSWT) for Lake Simcoe, Canada, 44° N 79° W (depth 25 m), showing that the greatest wind speed scaling, *u3* ($U_{\text{water}} = 1.62+1.17U_{\text{land}}$), in place of the unscaled wind speed, *u1*, reduces the daily 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 ($\alpha 1$) and light extinction coefficient derived from Secchi disk depth data (κ_{sd})

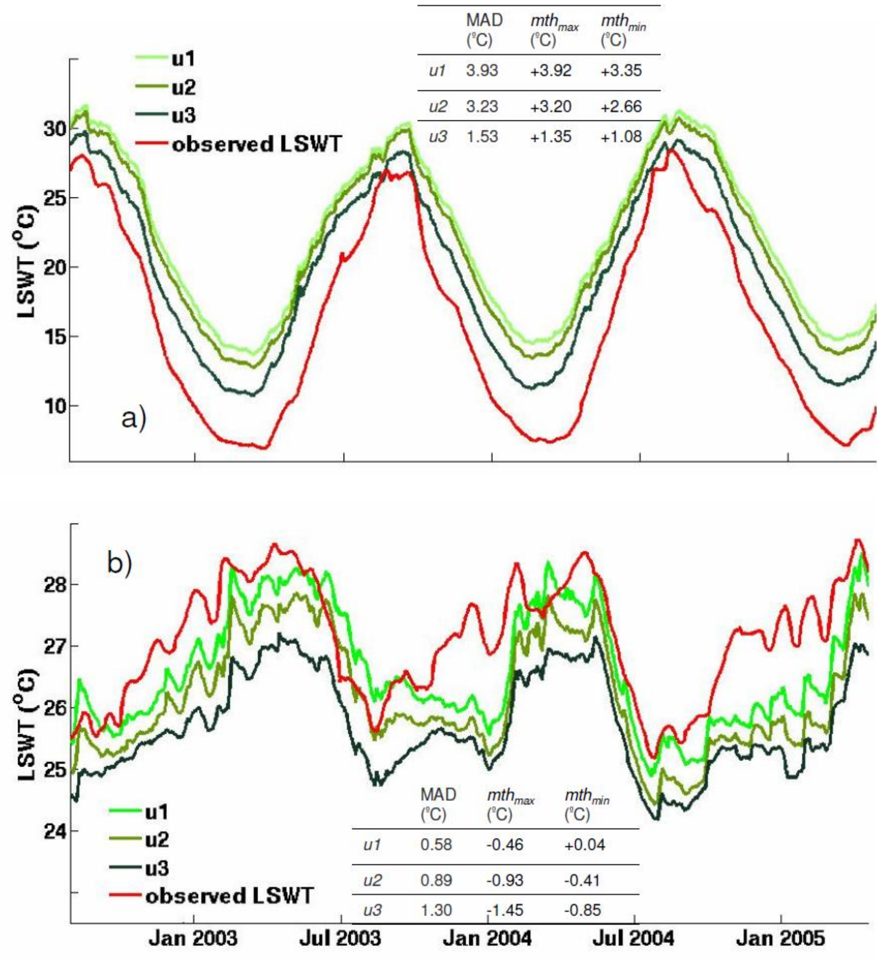

Figure 10 Effect of wind speed scaling on lake surface water temperatures (LSWT) for a temperate non-ice covered lake a) Lake Biwa, Japan (36° N 136° E) and for a tropical non-ice covered lake b) Lake Turkana, Africa (4° N 36° E) showing that the modelled LSWT for the temperate lake is better represented 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

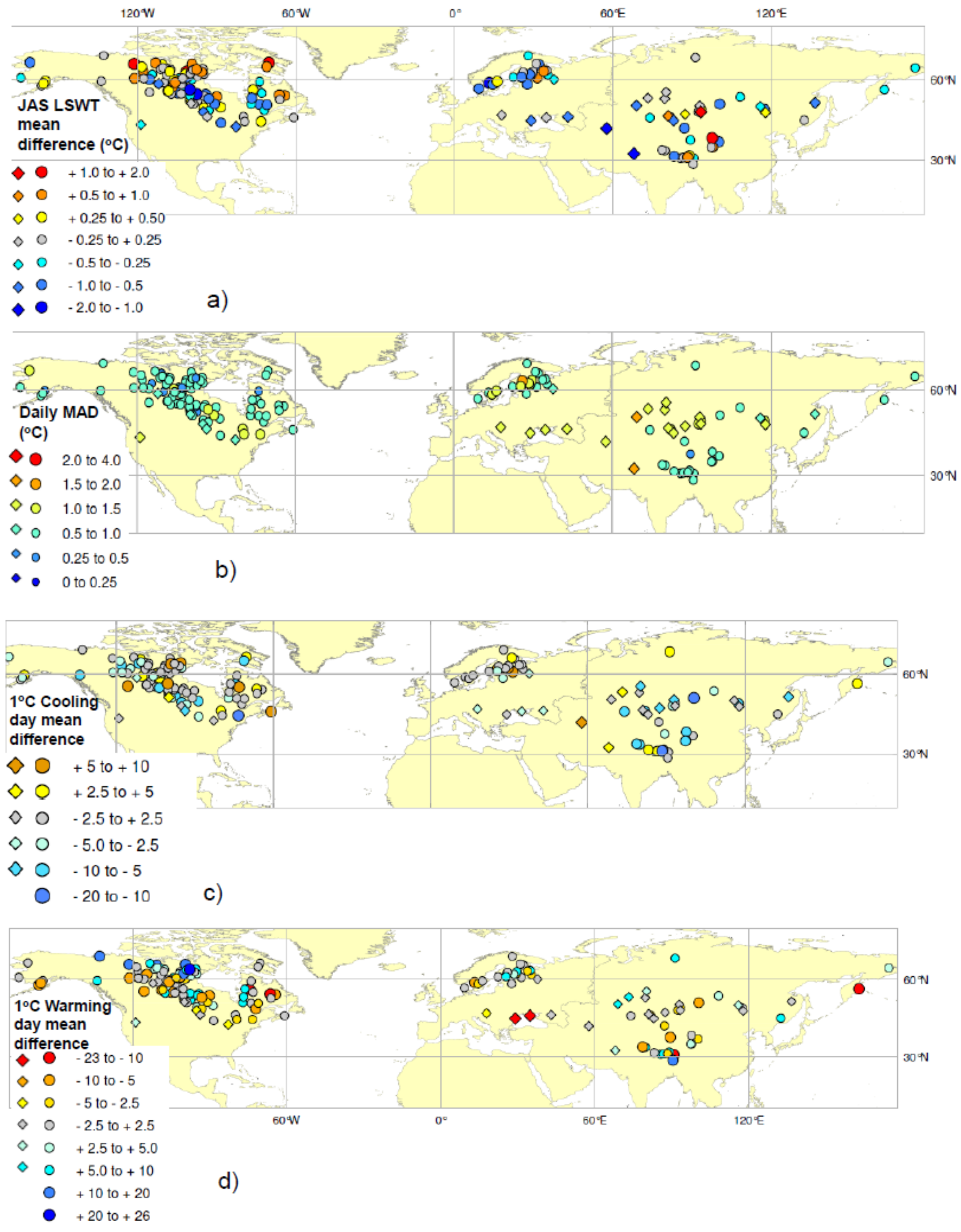

Figure 11 Tuning metric mean differences between modelled and observed LSWTs for all 160 lakes with seasonal ice-cover. The results for the 25 lakes tuned with modified tuning approach are marked by diamond symbols a) July August September (JAS) LSWT mean difference, b) Daily mean absolute difference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

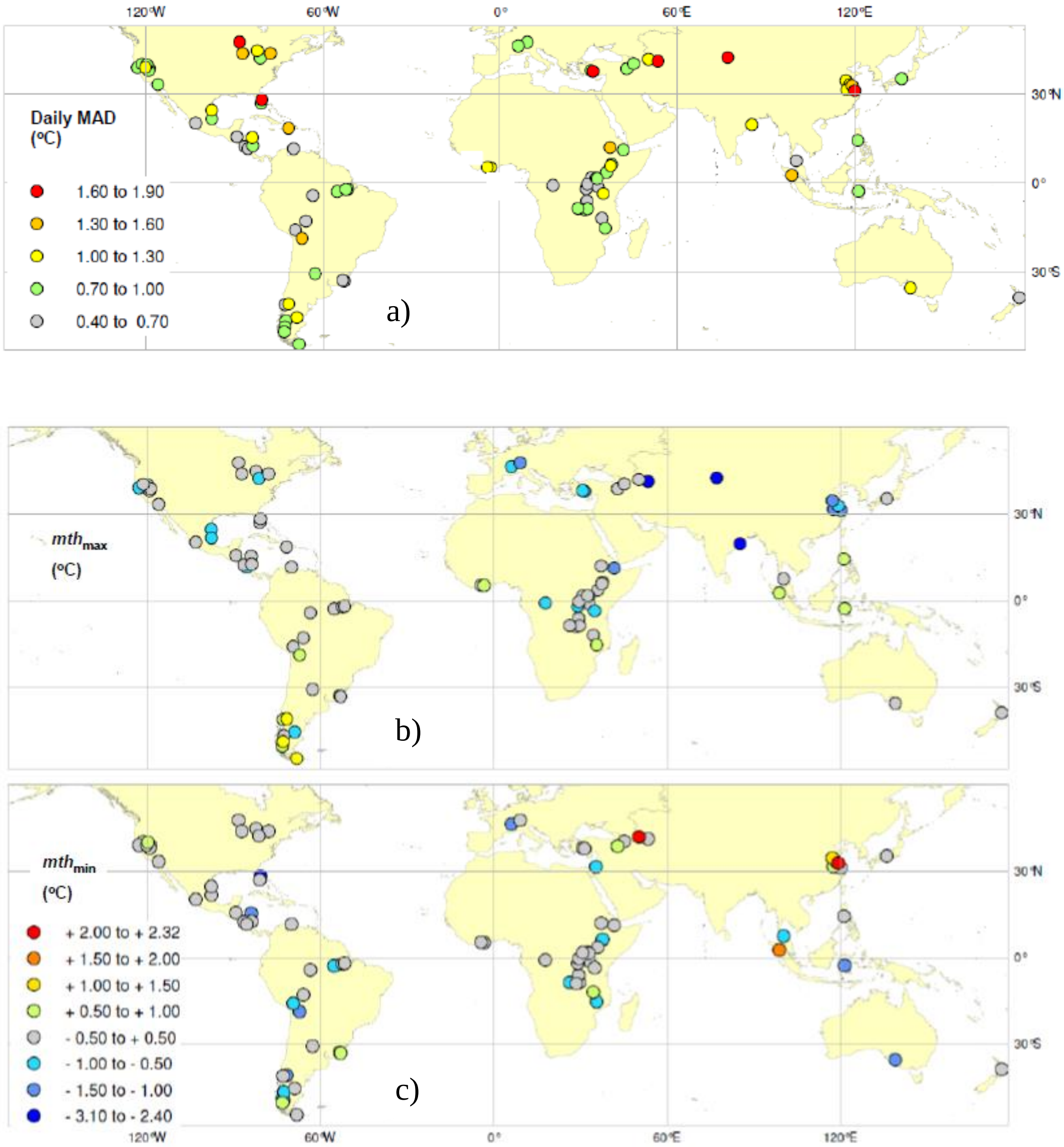

Figure 12 Tuning metric results for the 84 non-ice covered lakes a) Daily mean absolute difference (MAD) between observed and modelled LSWTs, b) mth_{max} and c) mth_{min}. mth_{min} (and mth_{max}) is the difference between the observed and modelled LSWTs for the month where the minimum (and maximum)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

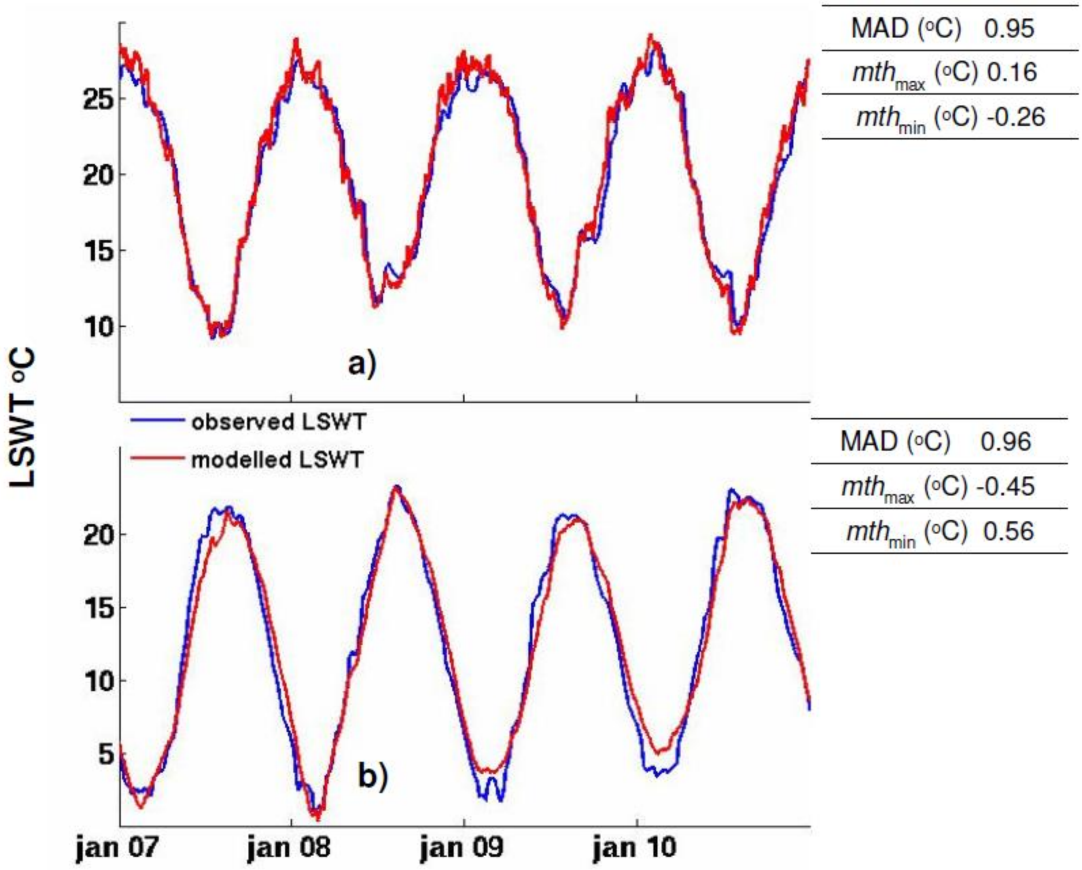

Figure 13 Observed LSWT versus tuned model LSWT for saline and high altitude lakes a) Lake Chiquita, Argentina (31° S 63° W, salinity 145 g L^{-1}) b) Lake Van, Turkey (39° N 43° E, 1638 m a.s.l., salinity 22 g L^{-1}).

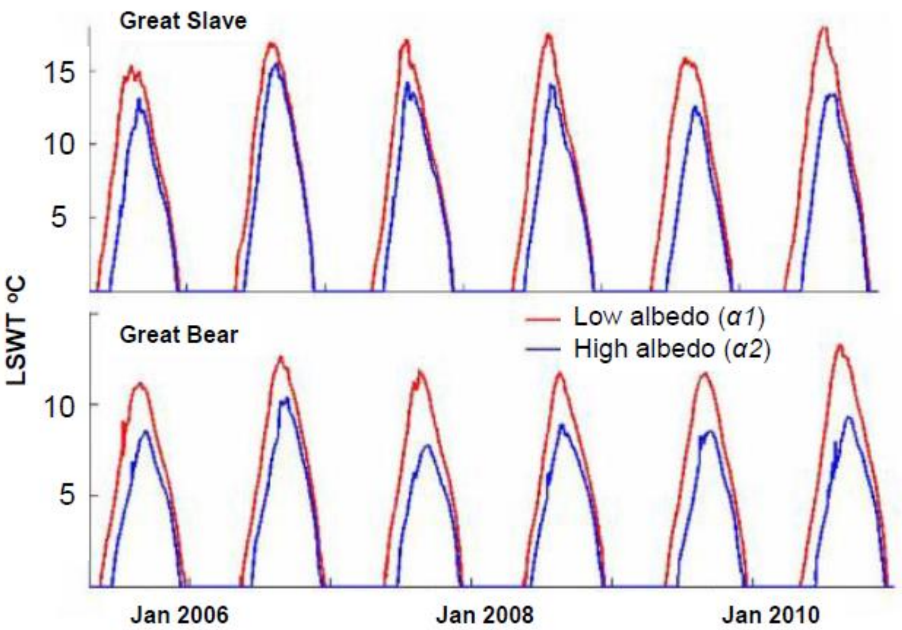

Figure 14 Lake surface water temperatures (LSWTs) for Great Bear (66° N 121° W) and Great Slave (62° N 114° W) modelled with low snow and ice albedo (default albedo, *α1*: snow and white ice = 0.60 and melting snow and blue ice = 0.10) and high albedo (*α2*: snow and white ice = 0.80 and melting snow 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

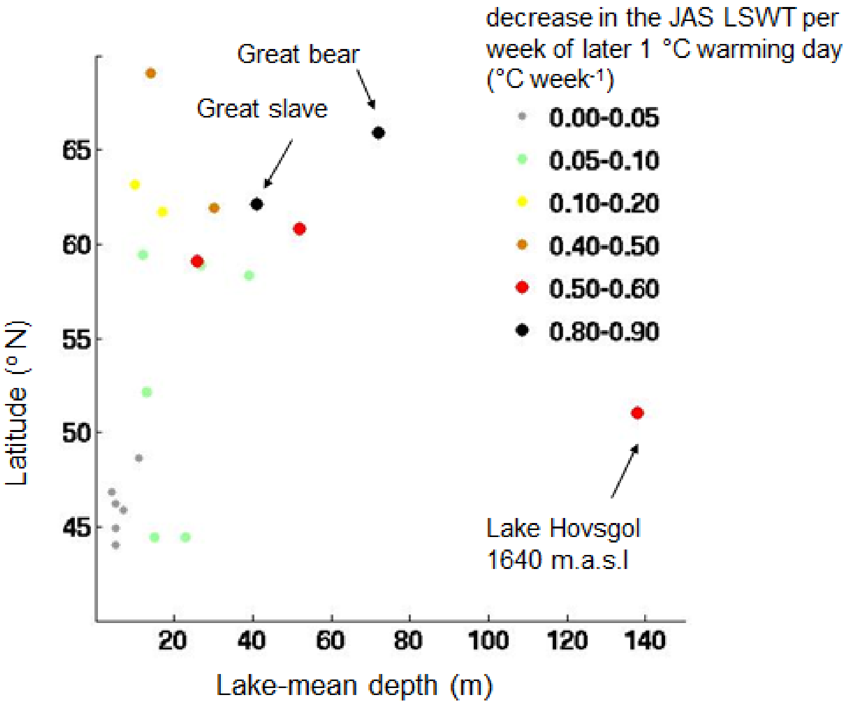

Figure 15 The relationship between latitude and lake-mean depth of the 21 trial seasonally ice-covered lakes and the decrease in the July August September (JAS) lake surface water temperature (LSWT) caused by the later 1 °C warming day (as a result of using a high albedo, *α2*: snow and white ice = 0.80 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.

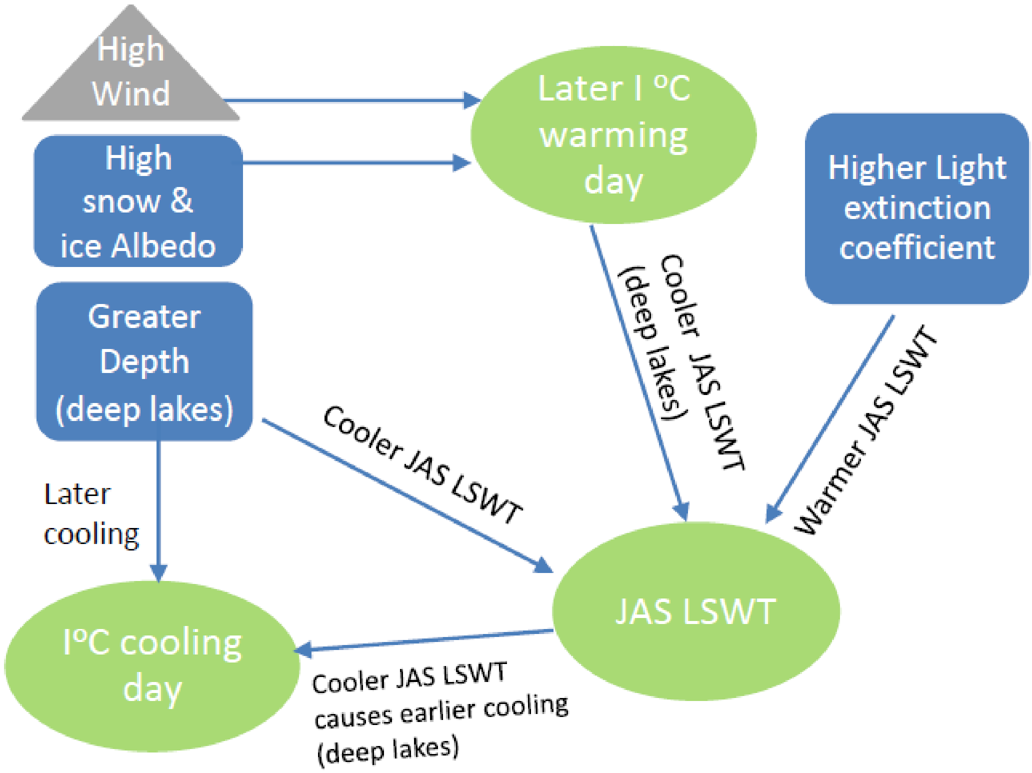

Figure 16 Schematic linking the interactions between the lake surface water temperature (LSWT) regulating parameters: lake depth (*d*), snow and ice albedo (*α*) and light extinction coefficient (*κ*), shown in squares and wind (shown in triangle) with the LSWT metrics: 1 °C cooling day, 1 °C warming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

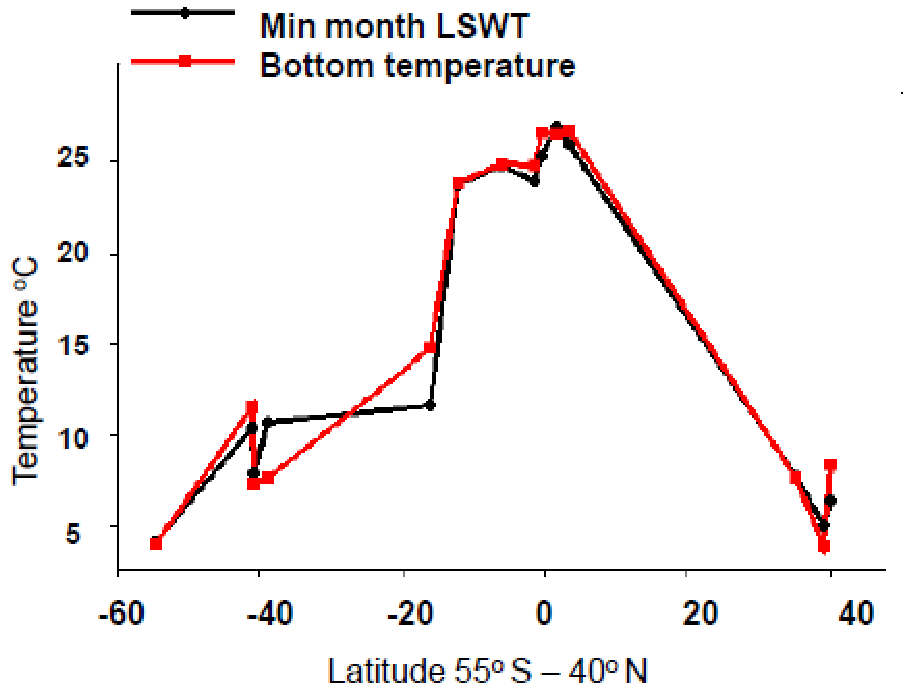

Figure 17 Comparison of lake-bottom temperatures during the stratification period, obtained from *FLake* model run using perpetual hydrological year, 2005/06 (Kirillin et al., 2011) and the monthly minimum climatology lake surface water temperature (LSWT) observations from ARC-Lake, for 14 deep (> 25 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.

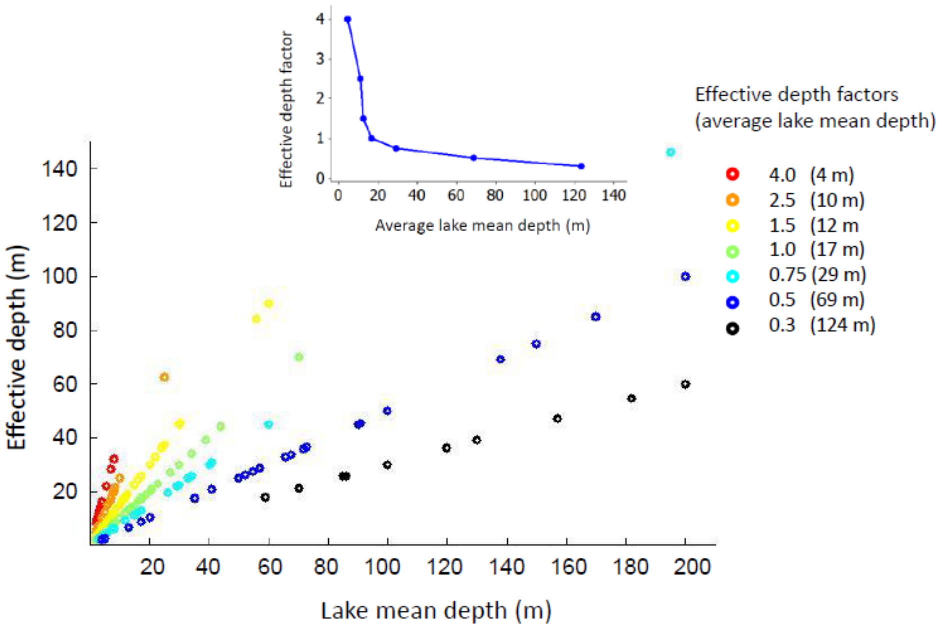

Figure 18 The lake mean depth vs. the modelled effective depth for 244 tuned lakes. Colour coding illustrates the effective depth factors. The average lake depth for each effective depth factor used in the tuning process is also given (insert). This figure demonstrates that deeper lakes are tuned to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