BOREAL ENVIRONMENT RESEARCH 15: 501–512 © 2010
ISSN 1239-6095 (print) ISSN 1797-2469 (online) Helsinki 29 October 2010

Coupling the 1-D lake model FLake to the community land-surface model JULES

Gabriel G. Rooney[1] and Ian D. Jones[2]

[1)] Met Office, FitzRoy Road, Exeter, EX1 3PB, UK (e-mail: gabriel.rooney@metoffice.gov.uk)
[2)] Centre for Ecology and Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster, LA1 4AP, UK

Received 30 Jan. 2009, accepted 25 June 2009 (Editor in charge of this article: Veli-Matti Kerminen)

Rooney, G. G. & Jones, I. D. 2010: Coupling the 1-D lake model FLake to the community land-surface model JULES. *Boreal Env. Res.* 15: 501–512.

Results are presented from the merging of the lake model FLake into the community land-surface model JULES. It is shown, by comparison with observational data, that the combined JULES-FLake model performs more realistically than JULES with its original or upgraded parametrizations for inland water. Tests against observations from lakes in the UK and Sweden show that JULES-FLake gives results for both midlatitude and arctic lakes which are comparable to the original lake model, FLake. The accuracy of JULES-FLake as a general model of the land surface is therefore enhanced. Differences in sign of the model errors in the prediction of lake-ice thickness indicate possible future directions for development and testing of these models.

Introduction

In the field of numerical weather prediction (NWP), the increase of available computational power has led to the development of NWP models with ever finer horizontal resolution. While the benefits of increasing resolution may be debated (e.g. Mass *et al*. 2002), it is nonetheless important to model the physical processes at a level of detail commensurate with the model resolution. Thus, an improved representation of the land surface is required at finer horizontal scales, in order that errors arising from the inaccurate representation of the surface fluxes are minimised. This requirement is met both by better mapping of the types of land surface, and by better parametrization of the processes by which these different functional types interact with the atmosphere.

The present study examines the performance of a model of one land-surface type, inland water, which often behaves very differently to the other range of surfaces. Thus, while "solid" land surfaces may consist of a covering of low thermal capacity, on top of a soil which can absorb heat at a rate limited by the efficiency of diffusive processes, a lake can store or release thermal energy more effectively. This is because the rate of heat exchange is often controlled by either wind-driven or convective turbulence in the lake body. As a consequence, the temperature of the lake surface can often remain well outside the range of the other types of land surface, with meteorological consequences e.g. as described by Schultz *et al*. (2004) and references therein.

In this study, we describe the impact of linking in the lake model FLake to the land-surface model JULES. It will be shown that this enhancement of the JULES model greatly improves its performance in the modelling of lakes, taking it to a level comparable with FLake. Since JULES has the inbuilt capacity to combine inland water with other land-surface types, the addition of a more realistic lake model increases its attractiveness as a general-purpose model of the land surface.

Models

JULES

JULES, the Joint UK Land Environment Simulator (http://www.jchmr.org/jules/index.html), is a stand-alone model of the land surface for use in the calculation of surface fluxes and temperature. It takes as input the initialisation data of surface temperature and soil temperature and moisture profiles, and forcing data of downwelling short-wave radiation, downwelling long-wave radiation, precipitation and near-surface (e.g. screen level) windspeed, temperature, humidity and pressure. It incorporates a model of surface heat flux, evaporation and plant transpiration, as well as an evolution of soil temperature and moisture. The soil properties are modelled on four soil layers of thicknesses: 0.1 m, 0.25 m, 0.65 m and 2.0 m. The thinnest layer is that at the surface, and layer thicknesses increase with layer depth (Best *et al*. 2005).

Version 1 of JULES, used in this study, is in most respects identical to the stand-alone version of MOSES, the Met Office Surface Exchange Scheme, which is used as the land-surface parametrization in the Met Office Unified Model for weather and climate modelling. MOSES is described in detail by Essery *et al*. (2001) and other studies of its performance as a model of the land surface have been described e.g. by Cox *et al*. (1998), Cox *et al*. (1999) and Rooney and Claxton (2006).

Bulk aerodynamic formulae are used in JULES to calculate the surface heat fluxes from the mean surface and near-surface values of temperature and humidity. These involve an exchange-coefficient formulation based on the momentum and scalar roughness lengths, z_{0M} and z_{0S} respectively, and the bulk Richardson number $\mathrm{Ri_B}$. The surface-exchange coefficient C_H is obtained as $C_H = f_h \times C_{Hn}$, where

$$C_{Hn} = k^2 \left[\ln\left(\frac{z_1 + z_{0M}}{z_{0M}}\right) \ln\left(\frac{z_1 + z_{0M}}{z_{0S}}\right) \right]^{-1}, \quad (1)$$

$$f_h = \begin{cases} \left(1 + 10\,\mathrm{Ri_B}/\mathrm{Pr}\right)^{-1} & \mathrm{Ri_B} \geq 0\,(\text{stable}) \\ 1 - 10\mathrm{Ri_B}\left(1 + 10\,C_{Hn}\sqrt{-\mathrm{Ri_B}}/f_z\right)^{-1} & \mathrm{Ri_B} < 0\,(\text{unstable}) \end{cases}, \quad (2)$$

$$f_z = \frac{1}{4}\left(\frac{z_{0M}}{z_1 + z_{0M}}\right)^{\frac{1}{2}}, \quad (3)$$

$$\mathrm{Pr} = \ln\left(\frac{z_1 + z_{0M}}{z_{0M}}\right) \left[\ln\left(\frac{z_1 + z_{0M}}{z_{0S}}\right) \right]^{-1}. \quad (4)$$

Here, k (≈ 0.4) is Von Karman's constant and z_1 is the height at which the near-surface forcing measurements are taken. The default value of scalar roughness length z_{0S} is $0.1 \times z_{0M}$.

The sensible-heat flux is calculated using a purely aerodynamic scheme. The latent-heat flux comprises aerodynamic evaporation from saturated surfaces, e.g. lakes, wet vegetation canopies and snow, as well as transpiration by plants and evaporation from bare soil, controlled by a surface conductance, g_S. The calculation of g_S uses a plant model taking wind, pressure, humidity, soil moisture, surface temperature and short-wave radiation as input, and is described by Cox *et al*. (1998).

Particularly relevant for the present study is the fact that JULES is a *tile scheme*, that is, it performs surface-flux calculations for nine different surface types (tiles) at the same point, and with the same underlying soil properties. It then can return fluxes and surface temperatures for each of these surface types, as well as the aggregate values calculated from a weighted average of the individual tile values. The weights correspond to the fraction of each surface type in the neighbourhood of the forcing-data measurement location.

The nine tiles in JULES correspond to five "vegetation" surface types (broadleaf and needleleaf trees, temperate and tropical grasses, shrubs) as well as the four non-vegetated types of urban cover, inland water, bare soil and land ice. The default JULES treatment of the inland-water tile is to give it the same, constant roughness length as bare soil ($z_{0M} = 3 \times 10^{-4}$ m), but a low albedo ($\alpha = 0.06$). It is allowed to evaporate at the maximum potential value without depleting the soil moisture store. Snow is allowed to accumulate on this tile, which only happens when the tile surface temperature falls below freezing, and the albedo increases with snow areal density.

An enhancement to the treatment of the lake tile in JULES has previously been used for some applications, which makes use of the "canopy" feature available on tiles. The presence of a canopy on a tile, such as trees or urban development, is represented by an intermediate layer of non-zero thermal capacity which intervenes between the atmosphere and the ground. This layer may be radiatively coupled (in the infrared) to both the atmosphere and the ground, and tile evaporative depletion is partitioned between canopy processes and soil storage depending on the canopy density. The canopy includes a canopy-water store for the interception and throughfall of rainfall, and this is drawn upon first for evaporation. In the JULES enhancement, the lake tile is assigned a canopy of maximal density and both large canopy water capacity and thermal inertia, making it in essence a "mini-lake". The effect of this canopy is to reduce the diurnal surface temperature range, since the canopy thermal store is able to exchange heat with the atmosphere more rapidly than the ground, which is limited to diffusive processes at the soil surface. When JULES is run with the 'mini-lake' configuration described here, the results will be referred to hereafter by the label JULES-ml.

FLake

FLake (Mironov 2008, Mironov *et al*. 2009, http://www.flake.igb-berlin.de/) is a 1-D lake model developed for NWP purposes. It is a "bulk" or "zone" model, that is, it divides the lake up vertically into regions (mixed layer, thermocline, thermally active layer of bottom sediments), and models the evolution of the large scale features (depth, temperature structure) of those regions via similarity formulations, returning the results in a small set of variables at each time step. It incorporates a lake-ice and snow layer capability. The main physical lake data to which the model is sensitive are the mean lake depth and the lake turbidity, parametrized by the extinction coefficient with respect to solar radiation.

The FLake release available for public use includes a surface-flux parametrization (SfcFlx), so that it can be run in stand-alone mode, and may be forced with the same data as that needed for JULES forcing. This facilitates the evaluation of the combined JULES-FLake model.

Observational datasets

Windermere

Windermere (54.35°N, 2.94°W) is the largest lake in the English Lake District, with an average depth of 21.3 m and a surface area of 14.76 km^2 (Ramsbottom 1976).

The Windermere dataset comprises lake temperature measurements at several depths between 1 m and 35 m, as well as meteorological records of windspeed, temperature, relative humidity, downwelling solar radiation and cloud cover. These data may be combined to provide an approximate timeseries of downwelling long-wave radiation in the manner described by Rooney (2005). Comparison of these long-wave data with output from the Met Office regional and UK models shows a high correlation (correlation coefficient value 0.77) and indicates that they are of sufficient accuracy for the present comparison. The pressure data were simply approximated by a constant value of 1000 hPa.

The dataset spans the whole of 2007, all at hourly resolution except for the cloud cover, for which the frequency of reports was twice daily.

A value of the extinction coefficient for Windermere of $\gamma = 0.36$ m^{-1} has been estimated from fortnightly Secchi depth measurements, following Kirk (1994).

Abisko

The Abisko dataset was obtained from the Abisko Scientific Research Station (Abisko Naturvetenskapliga Station, or ANS), on the south shore of lake Torneträsk (68.35°N, 18.82°E). This lake has an average depth of 52 m.

The Abisko dataset comprises meteorological data of windspeed, temperature, precipitation, relative humidity, pressure, downwelling short-wave radiation and downwelling long-wave radiation. These meteorological data are again at hourly resolution, and are accompanied by a daily classification of precipitation type. There are also measurements of lake-ice thickness at regular intervals during the ice season (approximately weekly), and the dates of lake freeze-up and break-up are recorded.

The data again span a whole year, starting on 1 August 2003. This late-summer start allows the simulation of a complete winter period.

To examine the effect of snow cover, the Abisko dataset was used twice, firstly in its original unmodified form, and secondly with the snowfall rate set to zero throughout. The results from these datasets will be labelled as Abisko and Abisko-nosnow, respectively.

Procedure and results

Integrating FLake into JULES

The new enhancement to JULES described here is the replacement of the lake tile with a coupling to FLake. The surface fluxes continue to be calculated using JULES flux parametrizations, so the SfcFlx section of FLake has not been used. The rest of the FLake model has been incorporated with no modifications other than the change of a logical value from the hard-wired default in order to inactivate the bottom-sediment thermal model. The example interface routine provided with FLake has been extensively adapted to become a JULES-FLake interface, however the number and types of the forcings passed to FLake have not altered. Thus, when run with a single lake tile, the coupled model is equivalent to the default use of FLake but with the SfcFlx package replaced by the turbulent-flux scheme of JULES and, when required, the FLake snow-layer scheme replaced by that of JULES.

The coupled JULES and FLake models will be referred to hereafter by the label JULES-FLake.

Interfacing

The "fixed" physical parameters required by FLake are the lake depth, the extinction coefficient, the lake fetch, the Coriolis parameter and the model time step. The additional forcing variables passed from JULES to FLake are the downwelling short-wave heat flux, S_d, the total heat flux from all pathways other than short-wave, H_d (i.e. the sum of atmospheric sensible and latent heat fluxes, plus the net long-wave flux) and the momentum flux.

The heat fluxes are partitioned in the way described because the short-wave (visible) flux is deemed to penetrate directly some depth into the lake, as determined by the extinction coefficient. The momentum flux is expressed as an aqueous friction velocity, simply obtained by stress matching at the surface, and so related to the usual (atmospheric) friction velocity by a factor of the square root of the ratio of the densities of air and water (e.g. Csanady 2001: section 1.7).

FLake returns the albedo, the average lake (water) temperature, the bottom temperature, the mixed-layer temperature, temperatures of the upper snow and ice surfaces, thicknesses of the snow, ice and mixed layers, and the "shape factor", which is related to the similarity profile of the thermocline temperature. These variables are either used in JULES calculations, or are stored by JULES from one time step to the next, or are output.

The JULES-FLake interface routine also calculates and returns a quantity R which is used to enhance the "ground" heat flux above the level expected from diffusive processes alone, if required. The details of this calculation are as follows. In each time step, JULES passes the value of the JULES lake-tile subsurface temperature T_{sLAKE} to the interface routine. This is the temperature at depth $(\Delta z_s/2) = 0.05$ m, i.e. equivalent to the centre of the top 'soil' level of thickness Δz_s, and JULES calculates it from the FLake output at the previous time step by a simple piecewise-linear temperature interpolation through the snow/ice/water temperature profile obtained from FLake.

The interface routine then calls FLake, which returns the arguments listed above. After this, the interface routine calculates the quantity

$$R = |G_{\mathrm{LAKE}}/\Delta T|, \quad (5)$$

where $G_{\mathrm{LAKE}} = H_d + (1 - \alpha)S_d$ is the total heat flux into the lake-tile surface, $\Delta T = T_w - T_{\mathrm{sLAKE}}$, α is the lake albedo and T_w is the temperature at the upper surface of the lake water, i.e. the surface temperature if the lake is not frozen or the freezing point if the lake is ice-covered. Both α and T_w depend only on the values returned by FLake.

The generation of this quantity R is a new feature of the modified interface routine, and it is used by JULES in the calculation of a Nusselt number Nu:

$$\mathrm{Nu} = \max(R\Delta z_w/2\lambda, 1), \quad (6)$$

where λ is the thermal conductivity of water and Δz_w is the depth of water within a depth Δz_s of the lake-tile surface. When the lake is unfrozen $\Delta z_w = \Delta z_s$, however if the lake has snow and ice layers on top then $\Delta z_w < \Delta z_s$. Typical magnitudes of Nu in the Windermere study of an unfrozen lake (*see* below) were in the range 10^2–10^4.

For unfrozen lakes the thermal conductivity of water used in the JULES calculation of subsurface heat flux is enhanced by a factor Nu. In this case, combining and rearranging Eqs. 5 and 6 we see that

$$G_{\mathrm{LAKE}} = \mathrm{Nu}\,\lambda[\Delta T/(\Delta z_w/2)]. \quad (7)$$

In the next time step, the initial JULES calculation of the subsurface flux, in the manner of Eq. 7, will therefore correspond to a surface temperature approximately equal to that coming out of FLake at the last time step. Note that the calculation of the ground heat flux in JULES is still done within a framework of a diffusion-type equation between the surface and the first "soil" level and so the coding changes in JULES are minimised. However the inclusion of Nu allows the heat flux and surface temperature to behave as though governed by the turbulent mixing processes which are parametrized in FLake.

For the transition states between frozen and unfrozen lakes, i.e. when $0 < \Delta z_w < \Delta z_s$, the thermal conductivity of the multiple layers is approximated by a depth-weighted average of the conductivity of each of the snow, ice and water layers, with only the water thermal conductivity enhanced by Nu. When $\Delta z_w = 0$, the factor Nu is not required and the subsurface heat flux into snow and ice is calculated with a purely diffusive model

The atmospheric fluxes for each tile in JULES are calculated using an implicit scheme, which generates the tile surface temperature at the same time. An initial estimate of the subsurface heat flux for each tile is used in this surface-exchange calculation, with the final value obtained following this calculation, as the resultant of the other fluxes at the surface. To preserve this separation of the atmospheric and subsurface fluxes, and the calculation of surface temperature along with the atmospheric fluxes, the surface temperature on the lake tile is not taken directly from FLake. However, as described here, the FLake value of the surface temperature is taken into account, via Nu, and used to calculate the initial estimate of the lake-tile subsurface heat flux.

Initialisation

FLake initialisation from JULES proceeds according to the general principle that little is known about the initial internal state of lakes from an NWP viewpoint. Therefore, the extra quantities that need to be specified have been kept to a minimum, with initial values approximated from known land values wherever possible. The surface values are most likely to be known, and so the surface temperature and albedo are taken directly from the usual JULES lake-tile initial values. The initial mixed-layer temperature is approximated by the initial temperature of the top soil layer (of thickness 0.1 m in JULES), and the initial mean lake temperature is approximated by the mean temperature of the soil column, bounded above by the initial mixed-layer temperature. Initial settings of the mixed-layer depth and shape factor are not expected to be known to any great degree of accuracy (without a previous run of the model), but in practice it is found that FLake adjusts the lake variables within a few time steps to attain a state of internal quasi-equilibrium.

None of the model runs described here begins with the lake tile in an ice-covered state, however for general use the upper ice surface temperature is initialised by the surface temperature if there is negligible initial snow cover, but it is set to the initial temperature of the top soil layer in the case of significant initial snow cover. Initial snow and ice upper-surface temperatures are both bounded above by freezing.

Surface heat flux

Ordinarily, the surface heat fluxes (into the ground) on each of the nine JULES tiles are summed with a weighting of tile fraction to produce the aggregate surface heat flux. This calculation is altered to exclude the ground heat flux on the lake tile, which is instead passed to FLake. The aggregate heat flux into the ground from the non-lake tiles is normalised by the total non-lake fraction.

Snow and ice

As with other tiles, the lake tile has the possibility of maintaining a snow layer on top. A test has been added to set the snow amount on this tile to zero if the lake ice is less than 1 mm thick.

JULES calculates snowmelt by diagnosing the surface temperature from the surface energy balance. If the surface temperature goes above freezing then some snow is melted in proportion, and the surface temperature is readjusted downwards accordingly. In the absence of snow, JULES has no equivalent mechanism to prevent the surface temperature of an ice-covered lake from rising above freezing, so a round-off has been added to perform this function at the end of the section of JULES code dealing with snowmelt. FLake adjusts the surface temperature in the same way.

FLake contains its own snow scheme, and when forced with the snowfall rate it will accumulate and melt a snow layer. Alongside this, FLake takes the presence (thickness, temperature etc.) of a snow layer into account in its calculations. The snow scheme of FLake has not been used for the accumulation of snow on the lake tile in JULES-FLake. The reasons for this are firstly, in a multi-tile configuration it would be inconsistent to use different snow schemes on different tiles. Also secondly, according to the FLake release notes the FLake snow scheme has not been thoroughly tested as yet, whereas that of JULES has been tested through implementation in operational NWP for several years.

In the FLake/JULES combination as presently coded, the flow of information about snow is purely one-way, from JULES to FLake. Thus the lake-tile snow thickness is calculated from the snow density and mass in JULES, and this is passed to FLake, which uses this information in its calculations. Any alterations to the snow layer within FLake are discarded by JULES. JULES does not calculate an internal temperature profile for the snow layer. Consequently, in the case of snow-covered ice, the temperature at the ice-snow interface output by FLake at one time step is returned to FLake at the next time step for updating.

FLake calculates the albedo of a frozen lake surface, α_{LAKE}, according to the formula

$$\alpha_{\mathrm{LAKE}} = \alpha_{\mathrm{w}} + \left(\alpha_{\mathrm{b}} - \alpha_{\mathrm{w}}\right) e^{\left[-C_{\alpha}(T_0 - T_*)/T_0\right]}, \qquad (8)$$

where α_{w} and α_{b} are the "white" and "blue" ice reference albedos with values 0.6 and 0.1, respectively, $C_{\alpha} = 95.6$ is an empirical coefficient, T_0 is the freezing point and T_* is the surface temperature at the previous time step. FLake does not modify the albedo to account for the presence of snow, however JULES-FLake takes α_{LAKE} as the snow-free value and modifies it to account for snow cover according to

$$\alpha = \alpha_{\mathrm{LAKE}} + (\alpha_{\mathrm{s}} - \alpha_{\mathrm{LAKE}})(1 - e^{-\mathrm{DS}}), \qquad (9)$$

where S is snow mass (kg m^{-2}), $D = 0.2$ m^2 kg^{-1} is an empirical coefficient and α_{s} is the maximum snow albedo which has a constant value of 0.8 for temperatures below –2 °C.

Results from the models

We performed several model runs for various combinations of models and datasets (Table 1). For the Windermere data, all the models were used, to compare the behaviour of each type at a UK lake for which freezing may be neglected in many years. The Abisko data were used primarily to compare the behaviour of JULES-FLake against that of FLake when significant lake freezing is expected to take place.

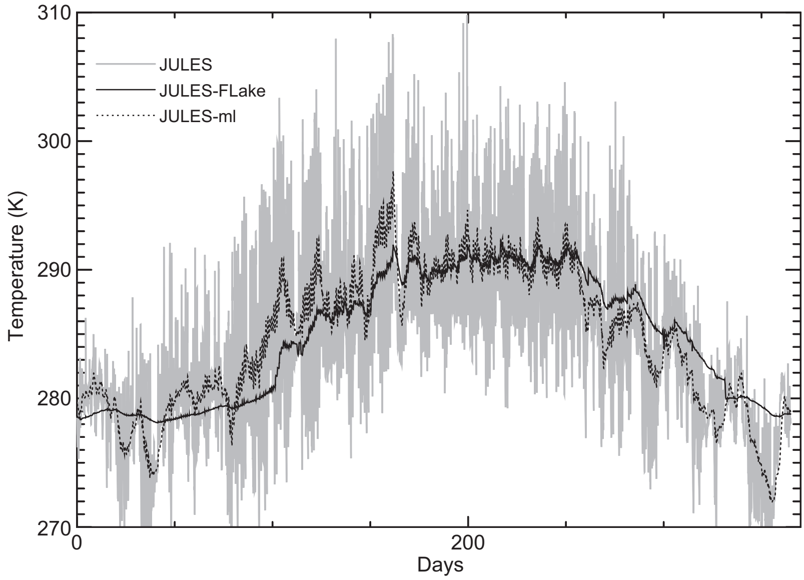

Fig. 1. Lake surface temperatures for Windermere calculated using the three JULES-based models, namely JULES, JULES-ml and JULES-FLake. The period covered is the whole of 2007.

In all the runs of the various JULES models described here, the lake-tile fraction was set to unity, since this provides the closest comparison with Flake. The FLake default value of the extinction coefficient, $\gamma = 3\ \mathrm{m}^{-1}$, was used for the Abisko runs.

Windermere

It is evident that in terms of the predicted surface temperature JULES produces an unrealistically large diurnal variation (Fig. 1). JULES-ml damps this behaviour somewhat, but still temperatures vary with a greater amplitude than those calculated by JULES-FLake over timescales longer than about 10 days. JULES-FLake shows two patterns of behaviour, firstly an extremely smooth variation of surface temperature in the half-year centred on winter when the lake is well mixed, and secondly a more responsive mode in the half-year centred on summer when the lake temperature stratification reduces the (aqueous) turbulent heat flux away from the lake surface. Each of these modes, but especially the well-mixed one, is less responsive to surface forcing than the behaviour of the other two models.

The comparison of the surface temperature from the two models JULES-FLake and FLake with data of the lake temperature at 1-m depth shows that the lower amplitudes of the temperature variations shown by these models are more representative of the actual lake behaviour (Fig. 2; note the reduced temperature scale of this plot compared with that in Fig. 1). It is notable that, despite a duplication of the lake model and the physical parameters for JULES-FLake and FLake, differences in behaviour remain, especially in the stratified mode. These must therefore be attributable to the differences in the atmospheric and surface flux calculations. On the whole, the behaviour of JULES-FLake appears to follow the data more closely. This is despite the atmospheric flux parametrization, at least over a non-frozen lake, being in some respects more sophisticated in FLake than in JULES-FLake. For example, FLake incorporates variable momentum- and scalar roughness lengths, whereas those of JULES are fixed over snow-free surfaces.

JULES-FLake demonstrates a stronger and more sustained well-mixed mode than Flake in winter, and also a deeper mixed layer in summer

Table 1. Model/dataset combinations used in this study.

	JULES	FLake	JULES-FLake	JULES-ml
Windermere	x	x	x	x
Abisko		x	x	
Abisko-nosnow		x	x	

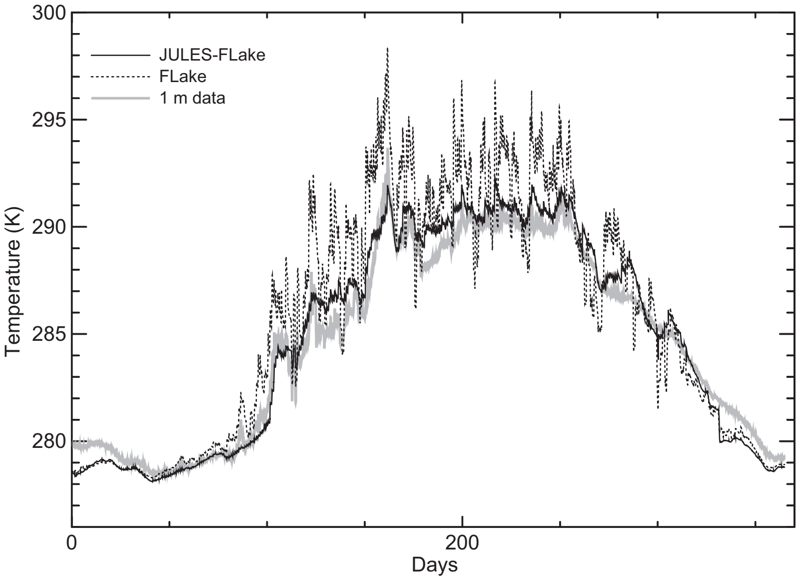

Fig. 2. Lake surface temperatures for Windermere calculated using JULES-FLake and FLake, compared with a point measurement of lake temperature at 1-m depth.

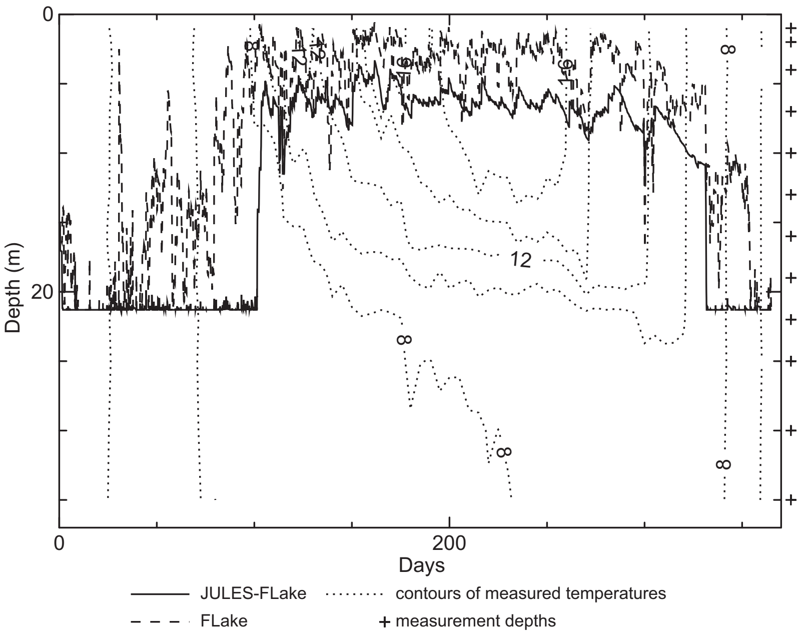

Fig. 3. Contours of the temporal evolution of measured lake temperature at Windermere, with the mixed-layer depths calculated using JULES-FLake and those calculated using FLake plotted on top. The contours are of temperature (°C), and are at two-degree intervals. The measured lake temperatures were sampled down from their original hourly frequency to a frequency of one observation every five days, in order to produce smoother contouring. The measurement depths are plotted as crosses along the right-hand edge of the plot.

(Fig. 3). The (atmospheric) friction velocities, u_*, in JULES-FLake and FLake were comparable in magnitude for values in the range $0 < u_* < 0.25$ m s^{-1} (approximately 85% of all values). Above this range, the FLake friction velocities were larger than those of JULES-FLake. This indicates that the deeper mixed layer in JULES-FLake is not attributable to wind-driven turbulence, but rather to a greater lake cooling in JULES-FLake compared to FLake, which is consistent with the surface temperature comparison. Figure 3 also illustrates the fact that the lake model is a whole-lake model, performing calculations in some averaged sense and bounded below by the mean lake depth (in this case 21.3 m), whereas clearly the point data at the measurement location can probe to greater depths. Thus, while the comparison with point data is an important check of the model, representation of the whole-lake behaviour in an NWP model is its primary purpose, and so divergence from point data is to some extent inevitable.

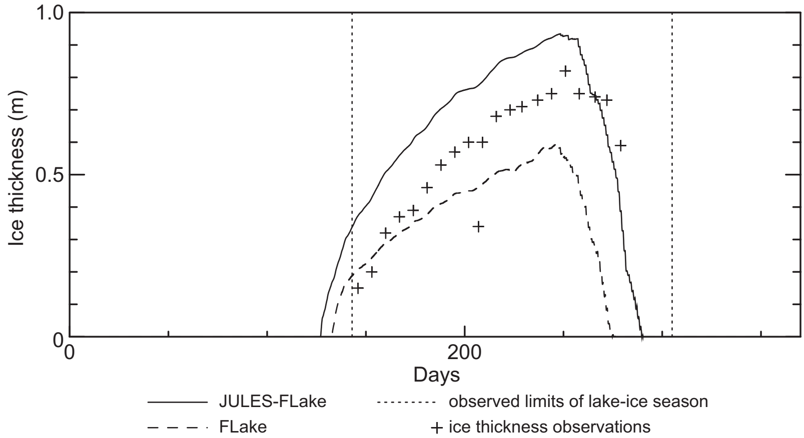

Fig. 4. Ice thickness measurements and model simulations for Lake Torneträsk (Abisko), during the year beginning in late summer, 1 August 2003. The vertical dotted lines on the plot mark the observed beginning and end of the lake-ice season.

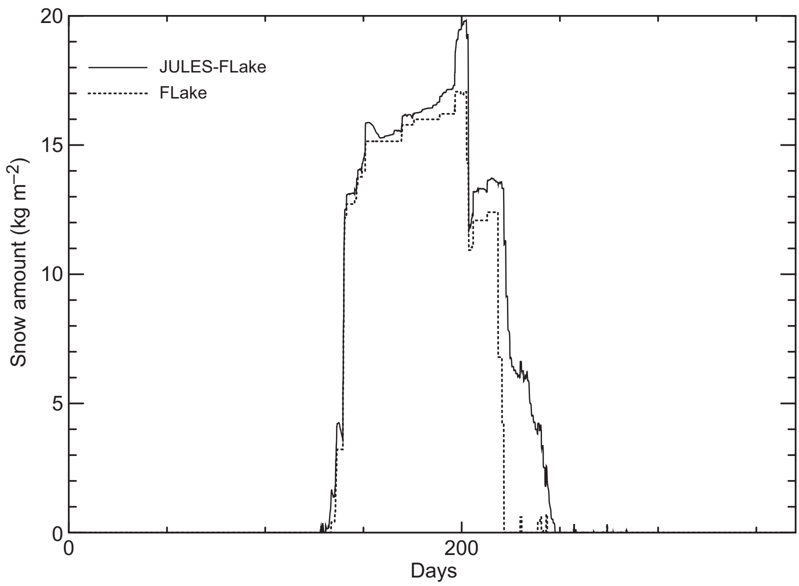

Fig. 5. Model predictions of lake-snow areal density at Abisko, during the year beginning 1 August, 2003. (Lake snow can only build up when the lake is frozen.)

Abisko

The Abisko cold-region dataset provides a further opportunity to test the models, this time in freezing conditions. To correctly predict both the timing of the lake-ice season and the evolution of the ice thickness, without any model tuning for the specific conditions, is an exacting test. Both JULES-FLake and FLake perform quite well, with similar thickness errors of order 20%–30%, although in opposite senses, at the time of maximum thickness (Fig. 4). The timing of the ice season is mostly within three weeks of the actual dates, except for the break-up date in FLake which is slightly farther out.

Regarding inter-model differences, as stated before, the lake model is the same in both cases, so the variation must come from elsewhere. The snow areal density predicted by the snow models of JULES-FLake and FLake, and the snow mass evolution is quite similar up to around day 200, after which the FLake snowpack melts perhaps twice as rapidly as that of JULES-FLake (Fig. 5). By day 200, the ice evolution in the models has already diverged, and so again it may be thought that the different treatment of the heat fluxes is responsible for the divergence of the models (Fig. 4).

As seen in Fig. 6, most of the surface heat flux (that is, the downward heat flux into the

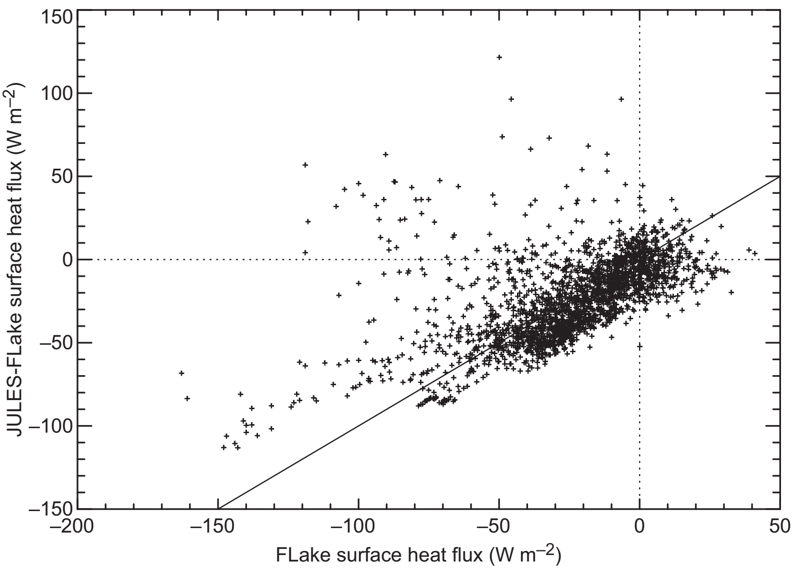

Fig. 6. Comparison of heat flux at the snow surface from the Abisko runs, plotting JULES-FLake against FLake. These data cover the period of non-zero lake snow cover in FLake. Positive values mean downward fluxes (i.e. into the surface), and vice versa. The solid line shows the 1:1 relationship, and the dotted lines indicate the axes.

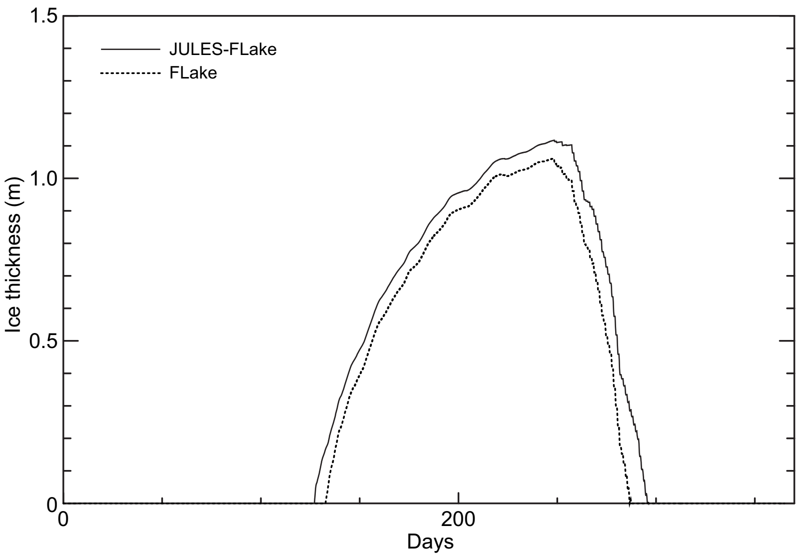

Fig. 7. Model predictions of lake ice thickness in the "nosnow" case. Note that the inter-model differences are much less than in the snowy case, *see* Fig. 4.

surface) during the period of FLake snow cover is in the third quadrant, indicating surface cooling in both models. Furthermore, the majority of these points lie below the 1:1 line, indicating greater net cooling of the surface by JULES-FLake as compared with that by FLake.

The importance of the surface (snow) heat flux may be demonstrated by the results of the Abisko-nosnow runs. Recall that in these runs the Abisko forcing dataset was used but with the snowfall rate set to zero throughout. The difference in the ice thickness is now much less than in the snowy case, showing that it is primarily the difference in the snow models which is responsible for the large differences in the ice evolution (Fig. 7). The remaining difference of a slightly thicker and longer-period ice cover in JULES-FLake is consistent with the cooler-surface results which were obtained with the Windermere data.

The JULES-FLake albedo in the snowy case is more often greater than that of FLake, which is to be expected since JULES-FLake increases the albedo in the presence of snow while FLake does not (Fig. 8). The consequent reduction of the downward net short-wave flux in JULES-FLake

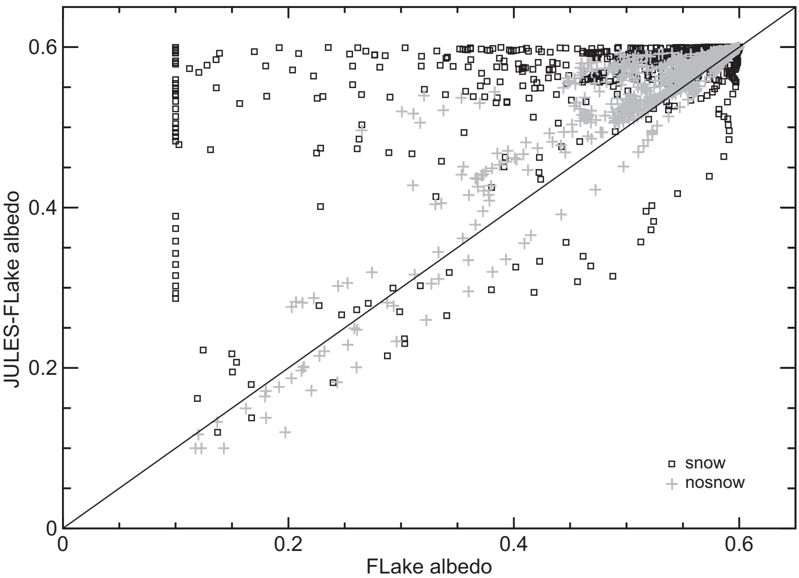

Fig. 8. Comparison of surface albedo from the Abisko runs, plotting JULES-FLake against FLake. These data cover the period of non-zero lake snow cover in FLake for the "snow" case, although they are plotted for both the "snow" and "nosnow" cases. Note that the data in the "nosnow" case lie more closely along the 1:1 line, whereas in the "snow" case the albedo in JULES-FLake appears to be appreciably greater than that in FLake for a large proportion of the time.

will be a contributing factor to the greater net surface cooling for this model. It appears that the albedos agree more closely in the snow-free case than in the snowy case.

The relative general cooling of the lake by JULES-FLake improves the prediction of the timing of lake-ice break-up, but worsens the prediction of the time of first freezing (Fig. 4). Therefore, neither a general cooling nor warming is required to improve upon the current performance of the lake model, but rather an increased seasonal dependence of the heat fluxes, such that cooling is decreased in autumn, delaying the freeze-up, and warming is decreased in spring, delaying the break-up. Such a change could be brought about either by enhancing the seasonality of the atmospheric-flux parametrization, for which some other physical justification would be required, or by increasing the thermal inertia of the lake in the model e.g. by increasing the lake depth used in simulations. The latter option indicates a possible direction for development of the lake model in the future.

Conclusions

The incorporation of the FLake lake model into the land-surface model JULES greatly improves its performance in the modelling of the inland-water land-surface type, and thus is expected to improve its representation of the land surface in general. JULES also benefits from the ability to produce new diagnostics, such as lake-ice thickness, which it could not with its original formulation. This opens the possibility of offering new model products which could be of benefit, for example in the prediction of trafficability of frozen lakes or rivers.

The performance of JULES-FLake has been shown to be broadly comparable to that of Flake coupled to its default surface-flux model, SfcFlx. It has been observed that, while the models may be of comparable accuracy, they can produce errors in the opposite sense when compared to observations, for instance in the prediction of lake-ice thickness. These divergences may be attributed to the differences in the snow or surface-flux parametrizations in the models. JULES version 1 has been used in these studies, however a new version of JULES will be released shortly, incorporating a more sophisticated model of the snowpack. FLake will be added to the latest version of JULES in the near future, and it is to be hoped that the improvements to the snow scheme will increase the accuracy of JULES-FLake in the frozen-lake regime.

Acknowledgements: Thanks to Martin Best, Andy Brown and Adrian Lock for much helpful discussion of this project.

Helpful comments from the editor and referees are also greatly appreciated. The provision of the Abisko data by the Abisko Naturvetenskapliga Station, and the assistance of Annika Kristoffersson of ANS, are gratefully acknowledged. Thanks are also due to Mr. B.C. Tebay of Ambleside for providing the Windermere cloud-cover data.

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