Coupling the lake model FLake to the JULES land-surface scheme

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1 Introduction

We describe the impact of linking in the lake model FLake to the land-surface model JULES, to improve the modelling of inland water in JULES. Inland water often behaves very differently to the other types of land surface. This is because the rate of heat exchange is often controlled by either wind-driven or convective turbulence in the water body, rather than by diffusive processes as in other "solid" surface types. 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.

2 Models

2.1 JULES

JULES, the Joint UK Land Environment Simulator, 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.

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).

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 nine tiles in JULES correspond to five 'vegetation' surface types 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.

2.2 FLake

FLake (Mironov, 2008) 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 timestep. 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 γ.

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.

3 Observational data

3.1 Windermere

Windermere (54.35N, 2.94W) 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. 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). 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.

3.2 Abisko

The Abisko dataset was obtained from the Abisko Scientific Research Station (Abisko Naturvetenskapliga Station, or ANS), on the south shore of lake Torneträsk (68.35N, 18.82E) in northern Sweden. This lake has an average depth of 52 m. The 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 August 1, 2003. This late-summer start allows the simulation of a complete winter period. The FLake default value of the extinction coefficient, $\gamma = 3$ m^{-1}, was used for Abisko in the absence of other information.

4 Procedure and results

4.1 Integrating FLake into JULES

The 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 significant modifications. The interface routine provided with FLake has been extensively adapted, 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**.

4.1.1 Interfacing

The 'fixed' physical parameters required by FLake are the lake depth, the extinction coefficient, the lake fetch, the Coriolis parameter and the model timestep. 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.

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 timestep to the next, or are output. After this, the interface routine calculates the quantity R, which is used to enhance the 'ground' heat flux above the level expected from diffusive processes alone, if required,

$$R = |G_{\text{LAKE}}/\Delta T| \tag{1}$$

where $G_{\text{LAKE}} = H_d + (1-\alpha)S_d$ is the total heat flux into the lake-tile surface, α is the lake albedo, $\Delta T = T_w - T_{s\,\text{LAKE}}$, $T_{s\,\text{LAKE}}$ is the JULES lake-tile subsurface temperature and T_w is the temperature at the upper surface of the lake water, i.e. the surface temperature T_* 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,

$$\text{Nu} = \max\left(\frac{R\,\Delta z_w}{2\lambda}, 1\right) \tag{2}$$

where λ is the thermal conductivity of water and Δz_w is the depth of water within a depth of the lake surface equal to the depth of the first soil level in JULES, Δz_s. 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 (1) and (2) we see that

$$G_{\text{LAKE}} = \text{Nu}\,\lambda \frac{\Delta T}{(\Delta z_w/2)} \tag{3}$$

The initial JULES calculation of the subsurface flux, in the manner of equation (3), is therefore based on a surface temperature approximately equal to that coming out of FLake at the last timestep. 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.

4.1.2 Snow

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.

FLake calculates the albedo of a frozen lake surface according to the formula

$$\alpha_{\text{LAKE}} = \alpha_w + (\alpha_b - \alpha_w)e^{(-C_\alpha(T_0 - T_*)/T_0)} \tag{4}$$

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 timestep*. 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

$$\alpha = \alpha_{\text{LAKE}} + (\alpha_s - \alpha_{\text{LAKE}})(1 - e^{-DS}) \tag{5}$$

where S is snow mass (in 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 colder than -2 C.

4.2 Results from the models

4.2.1 Windermere

Results are first presented from model runs with the lake-tile fraction in JULES-FLake set to 1, to provide the closest comparison with the configuration of FLake.

The comparison of the lake surface temperature from the two models JULES-FLake and FLake with data of the lake temperature at 1 m depth is plotted in figure 1. This figure demonstrates 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 unmodified JULES, which has been found to exhibit an unrealistically large diurnal temperature variation. It is notable that, despite a duplication of the lake model and the physical parameters for JULES-FLake and FLake, differences in behaviour remain. For example, JULES-FLake is generally cooler and less responsive than FLake, especially in the stratified mode. These differences must be attributable to the differences in the atmospheric and surface flux calculations.

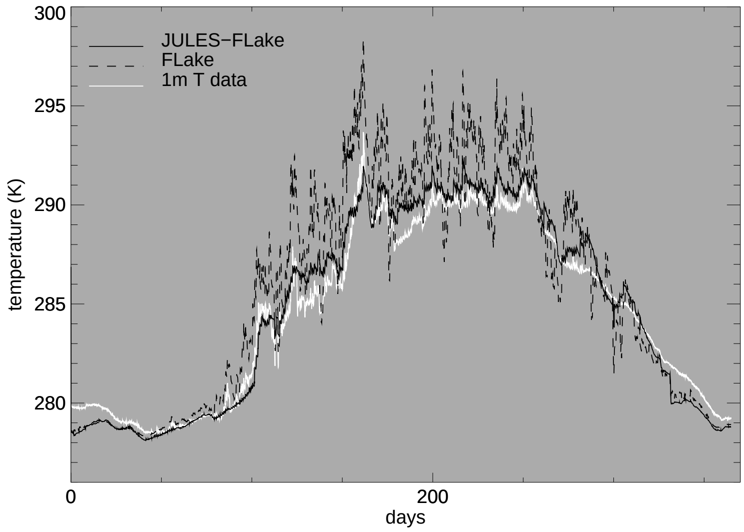

Figure 1: Lake surface temperatures for Windermere calculated by JULES-FLake and FLake, compared with a point measurement of lake temperature at 1 m depth.

The stratified and mixed modes of Windermere are illustrated in figure 2, which shows contours of the temporal evolution of the measured lake temperatures. Overlaid on these contours are the values of the mixed-layer depth as calculated by JULES-FLake and FLake. JULES-FLake demonstrates a stronger and more sustained well-mixed mode than Flake in winter, and also a deeper mixed layer in summer.

The majority of (atmospheric) friction velocities u_* in JULES-FLake and FLake were comparable in magnitude through most of their range. 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 2 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.

Finally, JULES-FLake was run with tile fractions corresponding to those in the Met Office North Atlantic and European (NAE) model at the Windermere location. These are approximately 72% grass, 10% inland water (lake) and 18% bare soil. Figure 3 shows the difference in the hourly grid-box mean (GBM) surface temperature T_* between JULES-FLake and a JULES control run, plotted against the absolute value of T_* from the JULES control run, with the results grouped by season. It is evident that the modified behaviour of the lake tile causes a reduction of approximately 3–4 K in the amplitude of the GBM surface temperature throughout the year.

4.2.2 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. Figure 4 shows that both JULES-FLake (run with a lake-tile fraction of 1) and FLake perform quite well, with similar

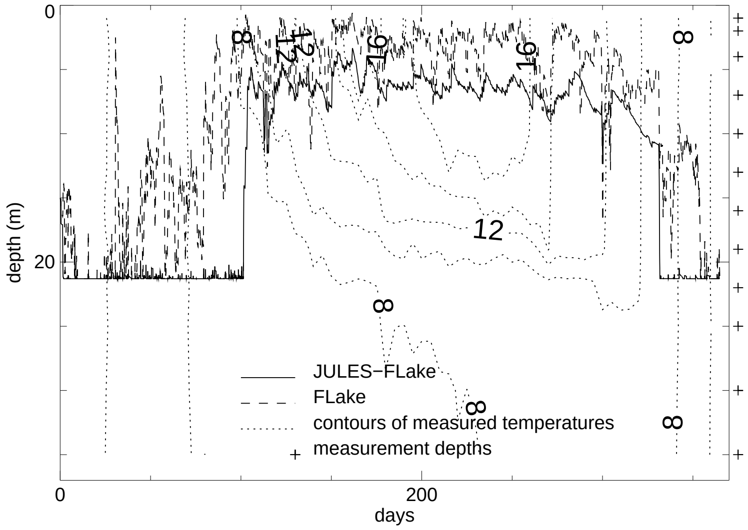

Figure 2: Contours of the temporal evolution of measured lake temperature at Windermere, with the mixed-layer depths calculated by JULES-FLake and FLake plotted on top. The contours are of temperature (C), at two-degree intervals. The measured lake temperatures were reduced to a frequency of one observation every five days to produce smoother contouring. The measurement depths are plotted as crosses along the right-hand edge of the plot.

thickness errors of order 20–30%, although in opposite senses, at the time of maximum thickness. The timing of the ice season is mostly within 3 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 mass evolution in the models is quite similar up to around day 200, after which the FLake snowpack melts perhaps twice as rapidly as that of JULES-FLake. However, figure 4 shows that by day 200 the ice evolution in the models has already diverged. In addition, it was found that in test runs with the snowfall rate set to zero, the difference in the ice thickness was much less than in the snowy case. Since the snow mass is similar, other aspects of the snow model, e.g. albedo, may be thought to cause this difference. It was found that 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. The consequent reduction of the downward net short-wave flux in JULES-FLake is a contributing factor to the greater net surface cooling for this model, and hence the observed difference.

5 Conclusion

The incorporation of the FLake lake model into the land-surface model JULES improves its performance in the modelling of the inland-water land-surface type. For lakes, the performance of JULES-FLake has been shown to be broadly comparable to that of Flake coupled to its default surface-flux model, SfcFlx. Differences remain between the two models, e.g. the treatment of atmospheric fluxes and snow albedo, and these contribute to differences in lake surface temperature and ice thickness. With a mixture of surface types including inland water, it has been shown that the inclusion of FLake in JULES can have a substantial impact on the diurnal amplitude of the predicted gridbox-mean surface temperature.

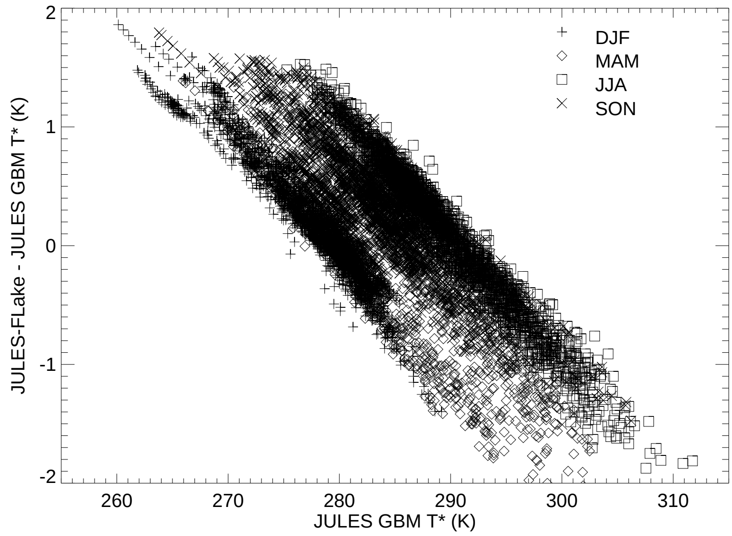

Figure 3: The difference between the hourly gridbox-mean (GBM) surface temperature T_* from JULES-FLake and JULES, plotted against that of JULES, for all of 2007. The data are plotted with different symbols for each season, as an indication of the mean annual variation. This shows that the amplitude of the JULES-FLake data is reduced compared to that of JULES. These results were obtained using the Windermere forcing data and associated surface cover distribution, with a lake-tile fraction of approximately 10%.

6 Acknowledgements

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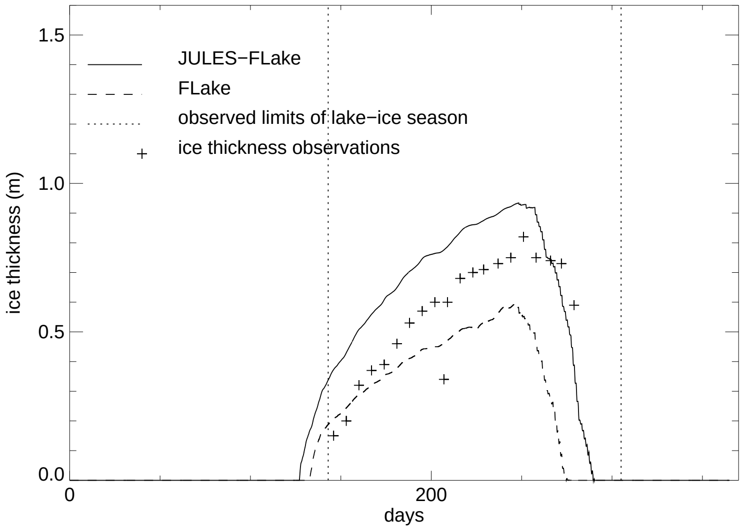

Figure 4: Ice thickness measurements and model simulations for Lake Torneträsk (Abisko), during the year beginning in late summer, August 1, 2003. The vertical dotted lines on the plot mark the observed beginning and end of the lake-ice season.

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