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First steps of a Lake Model Intercomparison Project: LakeMIP

Victor M. Stepanenko[1)], Stephane Goyette[2)], Andrey Martynov[3)], Marjorie Perroud[2)], Xing Fang[4)] and Dmitrii Mironov[5)]

[1)] *Moscow State University, Scientific Research Computing Center; Leninskie Gory, Moscow State University, building 4, RU-119991, GSP-1, Moscow, Russia*
[2)] *University of Geneva, Climate Change and Climate Impact, Battelle/D, 7 chemin de Drize, CH-1227 Carouge, Switzerland*
[3)] *University of Québec at Montréal, Canadian Regional Climate Modelling and Diagnostics (CRCMD) Network, 550 Sherbrooke Ouest, 19th floor, Montreal (Quebec), H3A 1B9, Canada*
[4)] *Auburn University, Department of Civil Engineering, Auburn Alabama 36849-5337, USA*
[5)] *Deutscher Wetterdienst, Frankfurter Str. 135, D-63067 Offenbach am Main, Germany*

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The state-of-the-art in one-dimensional lake modelling is briefly reviewed and the motivation for a Lake Model Intercomparison Project (LakeMIP) is presented. The objectives, methodology and implementation phases of the LakeMIP are outlined. Some results from the first intercomparison study are presented. The lake models used in the study range from a one-layer bulk model to finite-difference models with k-ε turbulence closures. All models tested proved to satisfactorily simulate the seasonal cycle of surface temperature in small Sparkling Lake (Wisconsin, USA). However, problems are encountered in representing vertical mixing through the lake thermocline and the evolution of the near-bottom temperature. Results from simulations of the surface temperature of Lake Michigan are in less gratifying agreement with observational data as compared with the Sparkling Lake test case, which calls for further investigation.

Introduction

It is a well-established fact that lakes play a key role in local weather conditions. As an example, one can mention severe weather events associated with large water bodies, such as the convective snowfalls frequently observed above and along the coasts of the Great Lakes in North America (Forbes and Meritt 1984, Norton and Bolsenga 1993, Niziol *et al*. 1995). However, small water reservoirs also have a significant impact on atmospheric processes where they modify the atmospheric boundary layer, thus affecting the magnitude and the incidence of turbulent fluxes at the water–atmosphere interface (Mahrt 2000). On the other hand, the hydrological conditions of lakes on a time scale of days and weeks are strongly dependent on weather conditions.

For longer time scales, the interactions between lakes and the atmosphere induce specific climatic conditions. These inland open bodies of water, seasonally covered by ice, strongly modulate atmospheric conditions, such as the diurnal cycle of the temperature, relative humidity, precipitation and deflection of the winds (e.g. Eichenlaub 1979). To illustrate climate-caused effects in lake hydrological regime, one may mention that "arid" climate lakes might lose much of their water content on a seasonal basis (e.g. Small *et al*. 2001) and on a multi-year time scale.

Hydrodynamics and thermodynamics provide a useful framework for developing numerical models of lakes and reservoirs. Such models have been applied in a number of limnological studies and, during the last decade, the growing capabilities of computing resources have facilitated a coupled atmosphere–lake modelling for predicting weather conditions, as well as in simulating climates.

However, the interactions between atmosphere and lakes are still often parameterized in a rudimentary way in these models. Until recently, prior to the seminal work by Bonan (1995), many studies of the hydrological impact of climate changes had been based on the one-way coupling between lake and atmospheric models, i.e. lake models run with atmospheric forcing computed by atmospheric models using simple surface schemes for regions with abundant lakes. Obviously, the use of the technique with the oversimplified lake effects in climate models has hindered many of the feedback mechanisms with respect to the computed atmospheric conditions.

The importance of inland water surfaces upon the local and regional climates has been demonstrated in numerical investigations using a land-surface model, including a subgrid parameterization for inland water coupled to a general circulation model (GCM) at a relatively coarse resolution of approximately 2.8° × 2.8° transform grid (Bonan 1995). Currently, the enhanced horizontal resolution of atmospheric models allows a large number of lakes to be explicitly resolved on the surface computational grid. However, parameterization of these lakes must be computationally cost-effective in order to warrant the efficiency of the integration schemes. Therefore, a reasonable compromise between numerical efficiency and physical adequacy has to be employed in lake and reservoir models, and one-dimensional models meet this requirement. A number of studies have proved that one-dimensional models are satisfactorily applicable for a range of lakes (e.g. Tucker and Green 1977, Boyce *et al*. 1993, Hamilton and Schladow 1997, Peeters *et al*. 2002, Gal *et al*. 2003, Yeates and Imberger 2003, Tanentzap *et al*. 2007, Mironov *et al*. 2010). A number of lake models have used a variety of approaches and formulations, such as simple parameterization based on similarity theory (Mironov 2008, Mironov *et al*. 2010), on mixed-layer concept (Stefan and Fang 1994, Goyette *et al*. 2000), on eddy-diffusion (Hostetler *et al*. 1993, Hostetler and Bartlein 1990), on bulk formulation (e.g. DYRESM, Imberger and Patterson 1981) and on the k-ε turbulence closure (e.g. Goudsmit *et al*. 2002, Stepanenko and Lykosov 2005). However, there is a considerable degree of simplification concerning each approach; lake models have often been designed and developed for given environmental applications, not covering all physical processes that are crucial in reproducing the range of lake–atmosphere interactions.

An intercomparison between lake models using observed data on a set of control lakes, representing different climate conditions and mixing regimes, should now be addressed to unravel this problem. The first steps in this direction have recently been undertaken by Perroud *et al*. (2009).

Similar problems have already been identified in the atmospheric and land surface modelling communities: Intercomparison projects, such as the Atmospheric Model Intercomparison Project (AMIP, Gates 1992), the Coupled Model Intercomparison Project (CMIP, Meehl *et al*. 2000), the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS, Henderson-Sellers *et al*. 2003) and the Snow Model Intercomparison Project (SnowMIP, Etchevers *et al*. 2004), have been implemented under the auspices of the World Meteorological Organization and Program for Climate Model Diagnosis and Intercomparison (WMO/PCMDI). The results of these projects demonstrate the usefulness of intercomparison initiatives to assist further development of respective areas in numerical modelling of weather and climate. Recently, an initiative for the development of a Lake Model Intercomparison Project, or LakeMIP, was initiated during the "Parameterization of Lakes in

Numerical Weather Prediction and Climate Modelling" workshop session held between 18 and 20 September 2008 in St. Petersburg (Zelenogorsk), Russia. The LakeMIP aims at addressing multiple research issues arising in the numerical modelling of atmosphere–lake interactions, which are useful not only for weather and climate matters but also for limnological studies.

Thus, this paper concisely describes the objectives, methodology and implementation phases of the LakeMIP.

An overview of one-dimensional lake models, the need for an intercomparison exercise

The concept of one-dimensional lake models may be obtained by assuming horizontal homogeneity for water state variables in the hydrodynamic and thermodynamic equations. This assumption is often valid, with some accuracy, for real lakes. However, there are special cases when it fails, e.g. when thermobar circulation develops. Another way of deducing one-dimensional equations is to integrate the hydrodynamic and thermodynamic equations in the horizontal plane, taking into account the boundary conditions at the lake shore. The resulting model is formulated in terms of horizontally averaged quantities. These two types of one-dimensional models constitute the class hereafter referred to as "finite-difference models" (Jöhnk and Umlauf 2001, Peeters *et al*. 2002) indicating that they explicitly resolve the vertical profiles of water state variables on a finite-difference grid. Finite-difference models solve the heat transfer equation by finite-difference methods conventionally using a down-gradient approximation to parameterize turbulence fluxes of heat and other quantities, and one or another approach for determining the eddy transfer coefficients. As for the latter, a number of diagnostic eddy diffusivity formulations have been proposed, employing the Richardson number (e.g. Henderson-Sellers 1985) that are computationally inexpensive. A more sophisticated way of calculating turbulent fluxes is to involve two-equation turbulence closures that are widely used in oceanic applications, e.g. k-ε parameterization.

Similar to bulk formulations for vertical transfer of properties in numerical atmospheric models that replace fine vertical resolution schemes, bulk formulations of lake models reduce the number of prognostic variables and computations required. Bulk lake models are based on the hypothesis that the integral amount of energy is made available for a slab of water. The simplest of these are one-layer bulk models that assume a complete mixing throughout the mixed layer (Goyette *et al*. 2000). A more sophisticated approach is implemented in the two-layer bulk model FLake, in which the structure of the stably stratified layer between the lower boundary of the mixed layer and the lake bottom, the lake thermocline, is parameterized using the concept of self-similarity of the temperature-depth curve (Mironov 2008, Mironov *et al*. 2010). The Minnesota Lake model MINLAKE (Riley and Stefan 1987) uses a finite-difference approach and eddy diffusion formulations to solve the vertical profile of water temperature, and then uses the bulk model approach to balance wind energy and thermal potential energy in determining the mixed-layer depth and temperature (Ford and Stefan 1980).

Finite-difference and bulk lake models have both advantages and limitations. Finite-difference models usually take into account the more sophisticated physics of mixing processes; however, they are of orders of magnitude more expensive computationally than bulk models. Bulk models have been usually designed for application in atmospheric models to provide the lower boundary condition of surface temperature and moisture needed to compute turbulent fluxes at the lake–atmosphere interface. Therefore, they have been mostly validated against the observational data at this interface, and demonstrate the accuracy of simulating the lake surface quantities close to that provided by finite-difference models. However, representation of the vertical temperature profiles in lakes by bulk models in some cases lacks important features crucial for limnological applications.

There are two physically-based parameterizations used in virtually all lake models: the turbulent mixing depending on the vertical density stratification and shear of momentum, and absorption of solar radiation through the water column. In a number of studies other physical effects have been included in one-dimensional models — partial ice cover, the effect of seiches (Goudsmit *et al*. 2002), bottom sediments (Mironov 2008) or soil layers underlying the bottom of the lake (Stepanenko and Lykosov 2005). More specific lake-processes have also been taken into account, for instance bubble plumes for mixing and aeration (Wüest *et al*. 1992). At the moment, these "ad hoc" parameterizations are not regarded as crucial in lake–atmosphere interactions; however studies of new issues in this area may result in their further development. As an example, the intensive methane emissions into the atmosphere observed over numerous boreal lakes in the permafrost zone (Walter *et al*. 2007) are worth mentioning. Numerical simulation of this process thus requires that a methane generation and transport module be embedded in a lake model.

Most lake models have been tested on limited sets of lakes, not covering the wide spectrum of climatic and limnological conditions. Usually, the lakes taken into consideration fall within a range of model applicability "area", while less attention has been paid to the cases where modelling results have deviated significantly from observation data. Hence, there is no clear understanding of the limits of applicability for one-dimensional models. In order to better define the advantages and limitations of one-dimensional model formulations, a systematic intercomparison of lake models, involving measured data, is therefore required.

The LakeMIP design

The goal of this project is twofold. The first is to assess the range of applicability of existing one-dimensional model formulations, i.e. their capabilities and limitations in reproducing lake–atmosphere interactions, as well as internal lake thermodynamics. This objective will include the identification of the key physical processes to be taken into account in lake models so as to further improve their performance in lake–atmosphere interaction and limnological studies. The second is to simulate the interaction mechanisms between lakes and the atmosphere in the framework of weather and climate models of different spatial domains and resolutions as well as dimensionality.

The project is intended to evolve in two phases:

1. During the first phase, LakeMIP1, the intercomparison of different one-dimensional models, using observations on a number of lakes representing a wide range of climate and lake mixing regimes, will be performed.
2. The second phase, LakeMIP2, will aim at studying the impacts of lakes on regional-scale weather and climate using coupled lake–atmosphere models.

Below we will consider the first phase of the project and provide some details. The set of models included in the intercomparison encompasses a variety of formulations (Table 1). The finite-difference models in Table 1 are marked by "k-ε" if they utilize the k-ε parameterization of turbulence.

The choice of lake sites for this intercomparison study should meet two requirements. The first is the availability of a complete set of measurements, including atmospheric forcing and vertical water temperature profiles. Atmospheric variables and turbulent fluxes should be measured directly above the water surface by buoys or by permanent raft stations, and in exceptional cases on the lake's shore. The second is that the chosen lakes have to represent a wide range of climatic conditions and limnological regimes. However, the number of lakes used for this intercomparison should allow for a rapid and clear analysis. Therefore, the choice of lakes has to be based on a classification covering a few types. The lake classification used in the project is based on a combination of climate conditions (characterized by latitude and altitude for simplicity) and the lake depth. It covers equatorial lakes, mid-latitude lakes (freezing and non-freezing), arctic lakes and high-altitude lakes. In each category, the shallow and deep lakes are considered. A special class includes very shallow lakes so as to include polymictic regime (several mixing periods per year) in the study. Some concrete examples of lake types to be used in the project are listed in Table 2. Two of those lakes may be regarded as special cases: a very shallow lake (Lake Kossenblatter in Germany) and some very large and deep lakes (Laurentian Great Lakes in North America). Lake Kossenblatter is regarded as being well-mixed several times a year (polymictic regime); hence relatively simple models (e.g. well-mixed models or FLake) are likely to represent this regime realistically. The Laurentian Great Lakes are large water bodies experiencing essentially three-dimensional circulations, such as seiches and thermobars that could not be explicitly represented by one-dimensional models. However, special attention will be paid in the case of the LakeMIP in order to address this situation, showing some of the limitations of one-dimensional lake model formulations. The matter of lake water turbidity effects will be considered in the project as well; the data from two lakes, different in transparency but similar in terms of other physical characteristics, will be involved in the intercomparison.

The first experiment of the project used the observed data from Sparkling Lake (Wisconsin, USA). This experiment clarified the proposed methodology (*see* the next section) and tested the performance of one-dimensional models for shallow dimictic lakes, common at mid-latitudes. This experiment has been completed, the results obtained highlight new problems in model performance (*see* "The discussion of the Sparkling Lake experiment results") prompting performance of additional model runs. The subsequent experiments will simulate one of the Laurentian Great Lakes, lying close to Sparkling Lake, which is characterized by similar climate conditions.

The *in situ* limnological and meteorological data from lakes for the first phase of the LakeMIP will be obtained partly from open sources and partly from the site members of GLEON (Global Lake Ecological Observatory Network) project by Kratz *et al*. (2006).

The methodology of intercomparison experiments

The results of lake model simulations (thermal profiles in particular) are controlled by: (i) physical parameterizations, (ii) the numerical scheme, (iii) external parameters, and (iv) initial and boundary conditions, the latter including solar and atmospheric downward radiation, momentum, sensible and latent heat fluxes at the lake–atmosphere interface. A "reasonable" intercomparison of lake models would assume that the differences in model results are only due to (i) and (ii); therefore the LakeMIP experiments will be conducted under the following conditions:

1. Lake models will use the same scheme for sensible, latent and momentum fluxes at the lake–atmosphere interface.
2. The optical parameters of water, ice and snow on the lake (albedos, long wave emissivities, extinction coefficients) will have to be common to all.
3. The initial vertical profiles of water properties have to be identical.
4. A unique initial water depth (local at the point of measurement, average or maximal for a given lake) and the morphometry described by its area-depth relation will be prescribed in all models.
5. The duration of the integrations will be fixed, thus allowing for statistical testing.

Table 1. The lake models in the LakeMIP.

Lake model	The type of model	Source
SIMSTRAT	finite-difference, k-ε	Goudsmit *et al.* (2002)
LAKEoneD	finite-difference, k-ε	Jöhnk and Umlauf (2001)
LAKE model	finite-difference, k-ε	Stepanenko and Lykosov (2005)
DYRESM	finite-difference	Imberger and Patterson (1981)
Hostetler's model	finite-difference	Hostetler *et al.* (1993)
MINLAKE96	finite-difference	Fang and Stefan (1996)
FLake	parameterized temperature profile	Mironov (2008), Mironov *et al.* (2010)
Goyette's model	mixed layer	Goyette *et al.* (2000)

Table 2. Some examples of the lake classification in the LakeMIP.

Location	Lake		Mixing regime	Lake average/maximal depth (m)
	deep or shallow	name (location)		
Mid-latitude (non-freezing lakes)	Deep	Geneva (Switzerland, France)	Monomictic	153/309
Mid-latitude (freezing lakes)	Deep	American Great Lakes (Unites States)	Dimictic	(19–147)/(64–406)
	Shallow	Sparkling Lake (United States, Wisconsin)	Dimictic	11/20
Arctic	Shallow	Toolik lake (United States, Alaska)	Dimictic	7/25
	Very shallow	Kossenblatter (Germany)	Polymictic	2/6

In practical terms, the intercomparison is configured as follows: The models are distributed among the project participants. Each will deal with their own set of models. The outputs of all models will be compiled through the website, then common diagnostics will form the basis of the intercomparison, and finally the results of intercomparison will be made available to participants.

The setup of Sparkling Lake experiment

Sparkling Lake is a relatively small (64 ha) freshwater lake in northern Wisconsin, USA. The maximal depth is 20 m, the average being 11 m. The observations of meteorological variables and a number of limnic characteristics, including water temperature profiles, are held here by the Trout Lake Station (North Temperate Lakes LTER: High Frequency Meteorological and Dissolved Oxygen Data — Sparkling Lake Raft, North Temperate Lakes Long Term Ecological Research program (http://lter.limnology.wisc.edu), NSF, Center for Limnology, University of Wisconsin-Madison).

In the current study, we chose the period 1 Jan. 2002–31 Dec. 2005 as the model integration period so as to assess the capability of models of adequately reproducing the annual cycle of water properties and lake–atmosphere interactions. The meteorological data used as inputs are hourly data that were partly acquired at the Sparkling Lake raft and partly at the nearby Woodruff airport. The five lake models were run in this experiment: FLake, Hostetler's model, LAKE, Simstrat and MINLAKE96. The Simstrat model was launched every year from 15 May until an ice-pack formed, typically by the end of December, since this model does not take into account ice and snow layers. The numerical experiments with average (11 m), maximal (20 m) and local depth (18 m) under the raft have been performed. For brevity, in this paper we discuss the results of experiments that have been run by setting the maximal depth only.

The optical parameters in lake models were unified (Table 3), except for the ice and snow albedo, since in the FLake and Hostetler models, the former is used to implicitly parameterize the effect of snow cover. The extinction coefficient for water, λ, is derived from the mean Secchi disk, z_{SD}, for Sparkling Lake, following the classical formula of Poole and Atkins (1929):

$$\lambda = k/z_{SD}, \quad (1)$$

where $k = 1.7$. The extinction coefficients for snow and ice are set to high values due to the absence of experimental data on this particular lake for these parameters.

The LAKE and MINLAKE96 models treat the snow cover explicitly, since the snow module exists in their codes. The FLake and Hostetler models parameterize the snow effect by appropriately varying the ice albedo, as mentioned above. The Simstrat model does not have the ice and snow modules; hence for this model only the simulation results for the open water season will be analyzed.

The sensible heat flux, latent heat flux and the flux of momentum in the Sparkling Lake experiment were calculated in each model by their "native" schemes due to the technical difficulties of implementing the unique flux scheme in all lake models. Therefore, the differences in modeling results discussed below, especially in terms of surface fluxes and surface temperature, are partially caused by different flux schemes. However, these should be of minor importance as compared with turbulent mixing parameterization in the temperature profiles calculation.

The bottom temperatures are to some degree defined by the bottom heat flux. The FLake model parameterizes the heat transfer in bottom sediments by the self-similarity approach similar to those applied in the water column. The LAKE model explicitly solves the heat transfer equation in the soil/sediments layer under a lake. The MINLAKE96 model explicitly solves the heat transfer equation for a sediment layer for all horizontal water layers (Fang and Stefan 1996a, 1996b), and applies appropriate boundary conditions to simulate sediment heat flux for small lakes (Fang and Stefan 1998). Other models assume a zero heat flux at the bottom.

The lake bathymetry expressed by the depth dependence of the area of horizontal cross-section of the water body is taken into account in the Simstrat and MINLAKE96 models. Other models do not use any information on the lateral sizes of the lake.

Neither vertical grid spacing nor the integration time step was prescribed for all the models. The results of model experiments were linearly interpolated from the model's grid to the regular vertical grid with a 1-m spacing every hour. The exception was the MINLAKE96 model, which integrates its equations with daily timestep, and hence provided the daily output.

The discussion of the Sparkling Lake experiment results

Due to the introductory nature of this paper, this section only analyzes the performance of lake models in simulating the surface temperature, surface fluxes and vertical temperature profiles, while the observational data on the number of other variables is available.

The water surface temperature considered here is the open water surface temperature during the ice-free period, and a temperature at the ice–water interface during winter. This is the mean temperature of the top layer in finite-difference models and the mixed-layer temperature in the FLake. It differs from the temperature of cool skin, since neither of the models used the parameterization of this layer. All the models designed for simulating ice-covered conditions performed satisfactorily well in calculating the surface temperature (Table 4). Note that, for the MINLAKE96 output, we calculated only the mean value since this output is the daily one as opposed that of other models and observations. The remarkable agreement between simulations and observations is partially caused by ~3.5 months of ice cover when the water surface

Table 3. Optical parameters in Sparkling Lake intercomparison experiment. m.d. = model dependent parameters.

Optical parameter	Water	Ice	Snow
Extinction coefficient (m^{-1})	0.27	10^7	10^7
Shortwave albedo	0.07	m.d.	m.d.
Longwave albedo	0	0	0
Longwave emissivity	0.99	0.99	0.99

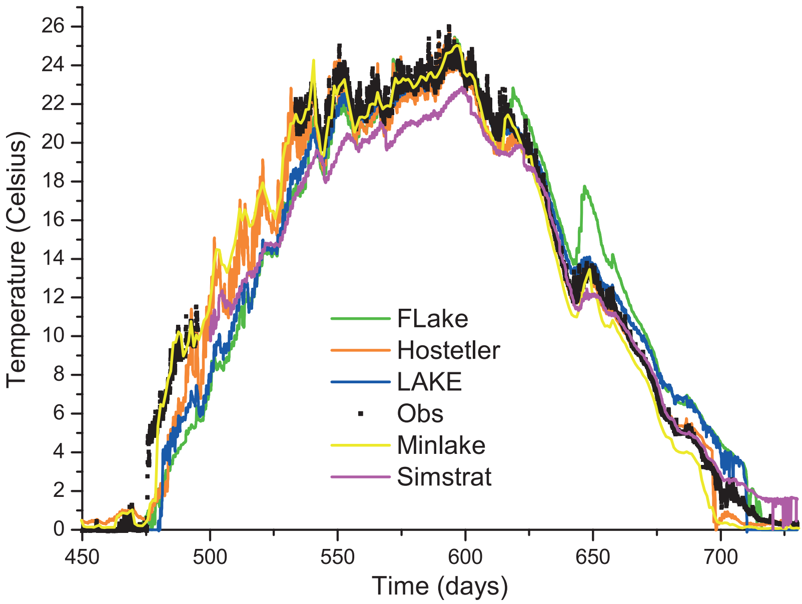

Fig. 1. Time series of Sparkling Lake modeled and observed water surface temperatures in 2003, (the days on the horizontal scale are counted from 1 January 2002).

temperature is maintained at the constant freezing point. However the figures of temperature throughout the rest of the year (Fig. 1) demonstrate an reasonable correspondence of calculated temperature dynamics to the observed one. An interesting point to be mentioned here is that both *k*-ε models, LAKE and Simstrat, significantly underestimate by 2–3 °C the surface temperature within the first half of all the four summers when the temperature systematically grows. We will address this issue below while discussing the vertical temperature profiles.

As for the sensible and latent heat fluxes (Tables 5 and 6) one may notice that the agreement between the observed and simulated time series is less compared with that of the surface temperature. This may be attributed to a number of effects that the surface schemes are not really representative and which are difficult to distinguish in the current study, e.g. the formation of internal atmospheric boundary layers at the lake shores and land covered by vegetation (Mahrt 2000), the water surface wave development, that is often far from the mature state (Wüest and Lorke 2003), etc. Note that all models overestimated the four-year mean latent heat flux from the lake by approximately 10 W m^{-2}, while the average sensible heat flux is reproduced quite well.

Table 4. Statistics for the time series of surface temperature (°C) in Sparkling Lake intercomparison experiment (2002–2005). n = 33 152 for all.

Source	Mean (min, max)	Correlation with measured data (r)
FLake	9.75 (0, 27.10)	0.988
Hostetler	9.59 (–0.01, 27.49)	0.995
LAKE	9.39 (–0.26, 25.71)	0.988
MINLAKE96	9.58	–
Measurements	9.41 (–3.87, 27.00)	–

We should consider the monthly averaged temperature profiles for March 2003 (Fig. 2) and June 2003 (Fig. 3). The results for this year are analyzed here, since 2002 is considered to be a spinup year. These two months represent the conditions of a late ice-covered period and the early-summer temperature rise period, respectively. The models captured well the temperature profiles formed towards the end of the ice-covered period, except for the FLake that produces a deep mixed-layer under the ice. The latter is due to the scheme for the mixed-layer depth calculation in the FLake which almost fixed the pre-ice value of this depth when the ice appears. The temperature profiles for June demonstrate the problem of both abovementioned *k*-ε models. They produce strong mixing, forming the deep mixed-layer, and leading to decrease

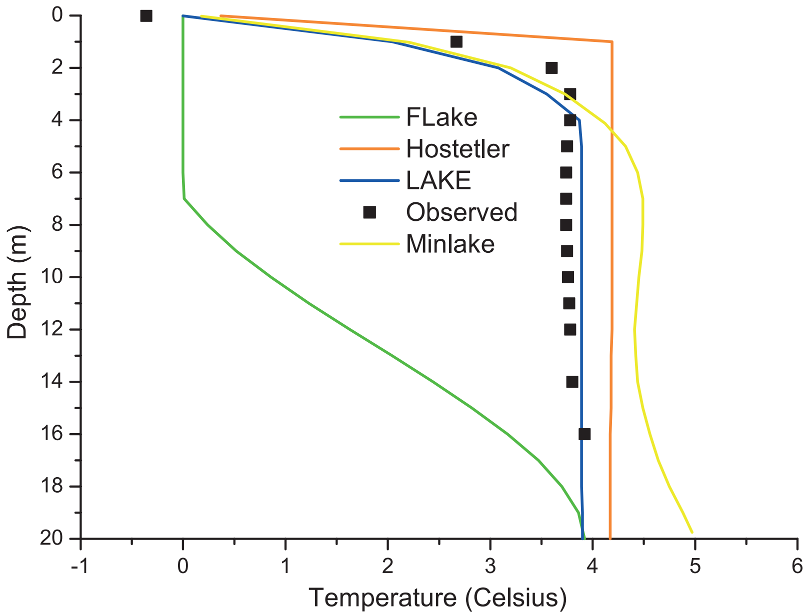

Fig. 2. Observed and simulated mean monthly temperature profiles in Sparkling Lake for March 2003.

of the surface temperature and increase of the temperatures below. This is most likely due to the formulation of those models which employ boundary layer approximations in TKE (turbulent kinetic energy) and dissipation equations that may become inappropriate for relatively small lakes.

Surface temperature simulations for Lake Michigan

According to the results presented in previous section and a number of earlier studies referenced above, one-dimensional models are capable of reproducing the shallow lake surface temperature quite well. This section describes a numerical experiment for the large and deep Lake Michigan aimed to test if the models' "performance" change significantly, as it is anticipated from physical argument (*see* "The LakeMIP design").

The numerical experiments were performed with three lake models: the LAKE model, Hostetler model and FLake. These were forced by perpetual-year atmospheric conditions. The atmospheric forcing used is that measured in 2002 above Sparkling Lake and at Woodruff airport lying in the vicinity of Lake Michigan. The surface temperatures calculated by the models and those obtained from buoys are shown in Fig. 4. As seen in this figure, there is a large discrepancy between the simulations of the surface temperature evolution provided by the three lake models and

Table 5. Statistics for the time series of sensible heat flux (W m^{-2}) to the atmosphere in Sparkling Lake intercomparison experiment (2002–2005). n = 32 874 for all.

Source	Mean (min, max)	Correlation with measured data (r)
FLake	12.55 (–410.17, 249.10)	0.735
Hostetler	12.88 (–220.86, 368.95)	0.712
LAKE	13.23 (–219.91, 364.58)	0.611
MINLAKE96	7.38	–
Measurements	12.20 (–246.80, 140.00)	–

Table 6. Statistics for the time series of latent heat flux (W m^{-2}) to the atmosphere in Sparkling Lake intercomparison experiment (2002–2005). n = 32 732 for all.

Source	Mean (min, max)	Correlation with measured data (r)
FLake	47.13 (–177.60, 334.12)	0.810
Hostetler	48.44 (–79.15, 385.15)	0.832
LAKE	41.98 (–113.59, 341.00)	0.765
MINLAKE96	43.87	–
Measurements	34.81 (–88.70, 224.90)	–

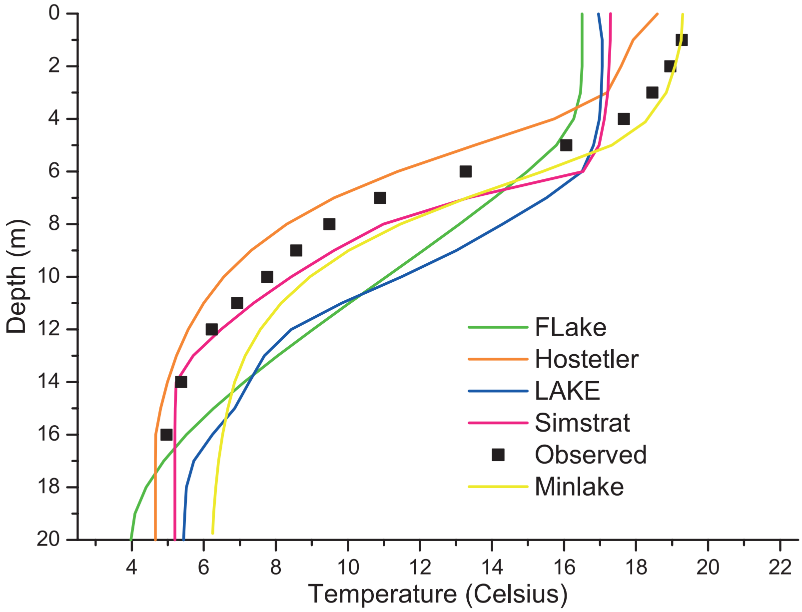

Fig. 3. Observed and simulated mean monthly temperature profiles in Sparkling Lake for June 2003.

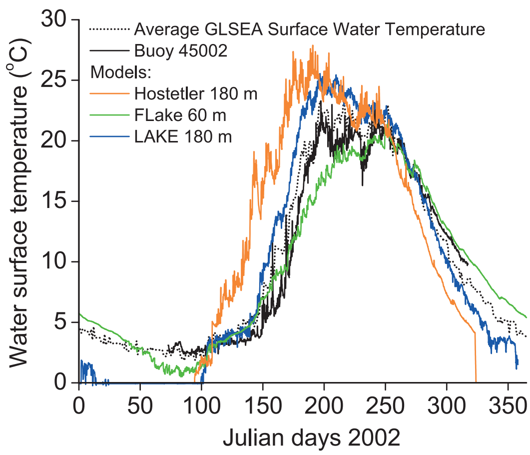

Fig. 4. The surface temperature of northern Lake Michigan (USA), simulated by LAKE, Hostetler and FLake models compared with measurements of the NDBC buoy 45002 and with the satellite-based GLSEA average surface water temperature (Schwab 1999).

observed values, which clearly shows that none of these models performs in a satisfactory manner for such a deep lake. The depth in the FLake was set to 60 m, since for larger values this model greatly smoothes out the variability of surface temperature. However, this setting allowed representation of ice-free conditions in winter, which is actually observed. The two finite-difference models do not reproduce this feature. Hostetler's model does not simulate the effect of a slow surface temperature increase under 4 °C due to the enhanced buoyancy-driven mixing. The LAKE model captures it, but it overestimates the rates of temperature rise in the early summer and the temperature fall in autumn — probably due to omission of some mixing mechanisms in the water column. The problems mentioned motivated us to perform a more comprehensive intercomparison study for this lake, involving three-dimensional models that account for 3D lake dynamics explicitly.

Outlook

To date, a large number of one-dimensional lake models have been developed and applied to many lakes, and some of these demonstrated sound skills in reproducing the lake–atmosphere interactions, as well as in simulating the evolution of the vertical water temperature profiles. However, to our knowledge, no single model has been shown to accurately reproduce the thermodynamic regime of a wider range of lakes in different climatic conditions.

During the last decade, some lake models were coupled to global and regional atmospheric models, and one should be confident that the lake parameterization used is not only valid for a specific lake regime. Hence, an intercomparison of lake model formulations is needed to identify the "areas of applicability" of these models, and to determine the physical processes crucial for their further development, either for atmospheric or for limnological applications.

This intercomparison project (Lake Model Intercomparison Project or "LakeMIP") was initiated during the "Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling" workshop held in September 2008 in St. Petersburg (Zelenogorsk), Russia. The proposed project will contain two phases:

1. The intercomparison of different one-dimensional lake models using the observation data from a number of lakes, representing a wide range of climatic and mixing regimes.
2. The coupling of these to the atmospheric models, either numerical weather prediction systems or climate models. This phase will study the impact of lakes on the weather regimes on a regional scale and on the climates of surrounding territories.

The first lake-model intercomparison study involving the observation data from Sparkling Lake (Wisconsin, USA) for the 2002–2005 period demonstrated good skills of one-dimensional models to reproduce the surface temperature. The agreement between modelled and observed data in terms of sensible and latent heat fluxes is not so close, characterized by correlation coefficients (r) in the range of 0.6–0.8. The general features of monthly vertical temperature profiles are well captured by the models. However, k-ε models produced extra mixing during May and June, with overcooling surface waters and heating water layers below. The FLake model generated the deep mixed-layer under the ice.

The numerical experiment with Lake Michigan demonstrated the large discrepancy between observed surface temperatures and those modelled by one-dimensional models. Although additional experiments are needed, this provides an argument that three-dimensional processes in large lakes are poorly parameterized in the models used in our study.

Further intercomparison studies within the LakeMIP will focus on deeper lakes, such as Lake Geneva or one of the Laurentian Great Lakes.

The progress of the project is shown at http://www.unige.ch/climate/lakemip.

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