Development of lake parametrization in the INMCM climate model

2016 IOP Conf. Ser.: Earth Environ. Sci. 48 012005

(http://iopscience.iop.org/1755-1315/48/1/012005)

Development of lake parametrization in the INMCM climate model

V Bogomolov[1,2], **V Stepanenko**[3,4] **and E Volodin**[5]

[1]Institute of Monitoring of Climatic and Ecological Systems, Siberian Branch of the Russian Academy of Sciences, Tomsk, 10/3, Academichesky ave., Russia
[2] V.E. Zuev Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk, 1, Academician Zuev square, Russia
[3] Research Computing Center, Moscow State University, Moscow, Leninskiye Gory str., 1, bld.4, Russia
[4] Department of Geography, Moscow State University, Moscow,Leninskiye Gory str., 1, Russia
[5] Institute of Numerical Mathematics, Russian Academy of Sciences, Moscow, Gubkina str., 8, Russia

Bogomolov@scert.ru

Abstract. Land surface schemes (LSS or terrestrial models) are a crucial component of both Numerical Weather Prediction (NWP) systems and climate models. An important land- surface type is lakes. This paper presents the mechanism of incorporation of a model LAKE into a coupled general circulation model of the atmosphere and ocean INMCM4, with a space resolution 2^o to 1.5^o and 21 levels in height, with two-way interaction. A new map for 14 land types distribution was created using a digital map of inland waters for the entire globe. The digital map of water bodies includes the fraction of lake area on the land surface, and the average depth of water bodies, both on the grid of the climate model. This digital map is based on a dataset consisting of 14 000 freshwater lakes. In order to increase the time step in the LAKE model, the k-ε parameterization has been replaced by the parameterization of Henderson-Sellers. With the amended INMCM4 model, numerical experiments were carried out to simulate global climate during the second half of the XX century. The effects of the new lake parameterization on the surface temperature and heat fluxes are analyzed.

1. Introduction

The land surface scheme (LSS) is a key component of numerical weather prediction systems and climate models. The permafrost areas are particularly difficult to simulate within the framework of the LSS. Firstly, permafrost can only be truly reproduced if the subsurface phase transitions as well as snow cover processes are correctly reflected in the model. The complexity of the problem is demonstrated by the huge spread of modern permafrost areas in the CMIP5 models ($4\text{-}25{*}10^6$ km^2, [11]). In this regard, we note that the LSS of INM RAS climate model is characterized by the maximal number of layers in the soil (23) among the CMIP5 models, allowing us to calculate in detail vertical heat transfer and the processes of freezing and thawing [12]. It is also important that the state of permafrost in LSSs is sensitive to small-scale features of the underlying surface, such as the presence of a layer of moss [13]. This indicates some prospects for further improving the quality of modeling of permafrost by including new effects on the underlying surface, such as a special model for snow in forest landscapes, improving the schemes of calculation of turbulent fluxes in the case of stable stratification [14].

It is important that the landscape of permafrost zones is characterized by a specific hydrological regime, expressed by an abundance of lakes and rivers. Lakes (mostly thermokarst) and wetlands occupy a significant part of Siberia (especially in Western Siberia). They significantly modify not only the thermodynamic interaction of the active layer with the atmosphere, but they are also an important source of greenhouse gases [15].

Lakes for a long time have not been recognized as important "actors" in the climatic system, as they occupy less than 4% of the land surface. However, the regional thermodynamic and dynamic effects of lakes on weather and climate are important for Canada, Finland, Western Siberia, and some other regions [1], [2], [3]. This motivated the inclusion of thermodynamic models of lakes in many weather systems and climate models [2], [1], [4], [5], [6]. Simultaneously with increasing knowledge on the significance of lakes for the current and future climates, several attempts have been made to develop lake models including not only thermodynamics and turbulence, but also biogeochemistry to simulate CH_4 and CO_2 in natural waters [8], [16], [17], [18].

In a coupled model of the general circulation of atmosphere and ocean, INMCM4, a participant of the CMIP5 experiments [19], the land cell can contain the following types of surface: vegetation, bare soil, snow and inland waters. The surface temperature, the sensible and latent heat fluxes from these four types are evaluated separately. The fluxes over an inland water body, as in the case of water droplets trapped by vegetation, are calculated under the assumption that the humidity of the air above this surface is saturated, but the layer of water does not have its own heat capacity. In addition, the soil under the different land surface types has the same vertical profiles of temperature, humidity, and ice concentration. It is quite a rough approximation for lakes, because the nature of the vertical heat exchange there is fundamentally different from that of the soil. Essentially, the same parameterization is used for wetlands. This leads to an inaccurate assessment of the role of lakes and wetlands in the formation of the regional climates of northern regions.

2. The components of a new lake parameterization for a climate model

To account for heat capacity of water bodies, turbulent heat transfer in lakes, and their contribution to the latent and sensible heat fluxes from the surface to the atmosphere, a special code inside the Earth system model INMCM4 has been developed. It includes a parameterization of lake thermo- and hydrodynamics, LAKE, [16] and detailed digital maps of the land waters surface fraction, and their depth (http://www.flake.igb-berlin.de/ep-data.shtml).

2.1. Lake depth, lake map (global data)

A digital map of water bodies was created to include two 2D arrays on the grid of the climate model (Figure 1): the fraction of a cell area occupied by the water surface and the average depth of water bodies in the cell when the cell contain more than 5 percent of the lakes, while the Lake digital map includes all lakes from a database. This digital map was developed using a dataset that includes about 14,000 freshwater lakes with data on their depths [9].

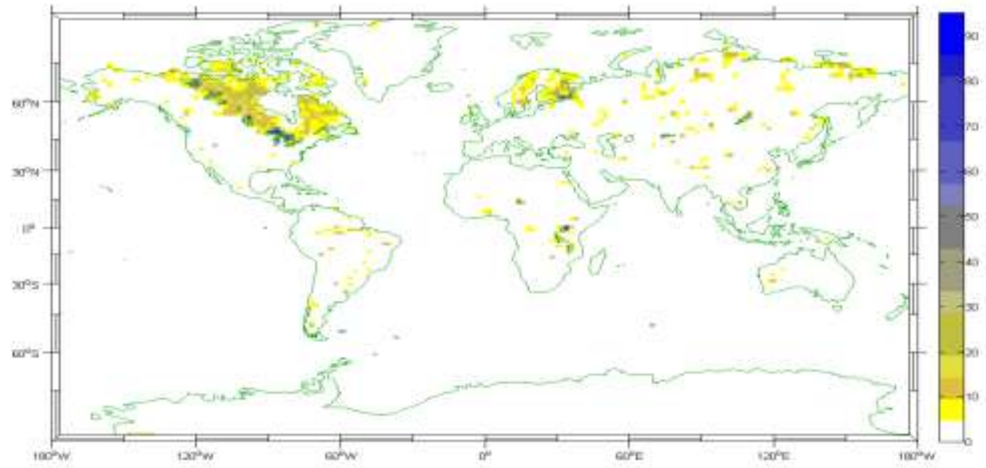

Figure 1. Map of water fraction in land cells of the INMCM4 model, %.

The previous mask of land surface types in INMCM4 included 13 types [20], the 13-th type corresponding to "wetlands", which included lakes inter alia. On the basis of the digital map of water bodies and the old land type mask, a new mask has been formed, comprising 14 types, where the 14-th type is lakes. At the same time, the fraction of lakes added to the 14-th type was excluded from the 13-th type. The fractions of other types are adjusted using a weighting function. In the old mask 1,018 cells included lakes, whilst in the new - 2422 cells (Figure 2). This new mask is generated using a developed suite of FORTRAN programs. This software package allows us to form a mask with the addition of a new type and correcting the fractions of the existing types using a weight function. It also meets any desired spatial resolution of the output data.

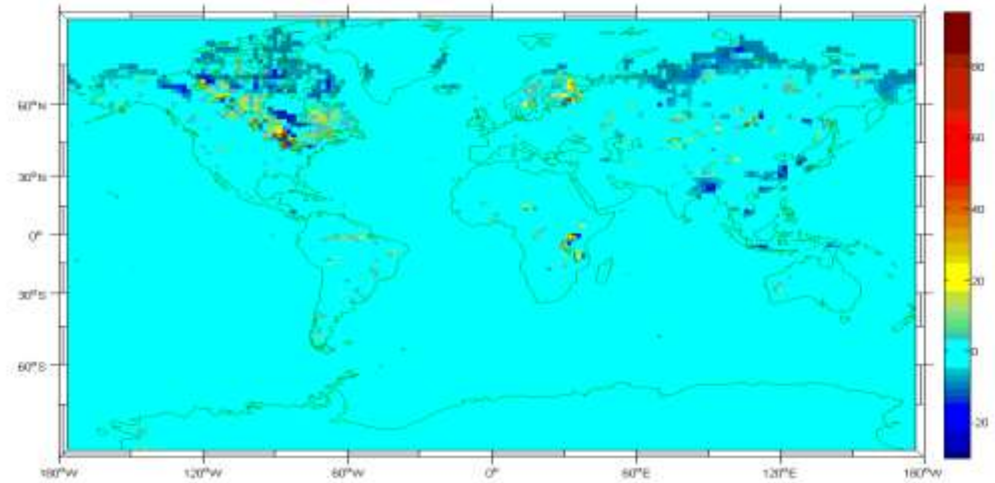

Figure 2. Difference between the lake fraction in the new mask and that in the old mask.

2.2. Parameterization of vertical diffusivity, convective adjustment scheme in the case of unstable stratification for lakes with high water transparency

In order to couple the models INMCM4 and LAKE, it was necessary to ensure in the LAKE model the same time step as in the climate model (1 hour). For this purpose, in the lake model, the time step-restricting k-ε turbulence closure [21] was replaced by parameterization of vertical diffusivity of Henderson-Sellers [10]. Before this replacement it had been shown that the difference in the surface heat fluxes and in the thermal regime of a lake caused by using these turbulent mixing schemes is small.

The numerical experiments with the lake model using the Henderson-Sellers parameterization have shown that mixing in water occurs only in cases of neutral and stable stratification, while in the case of unstable stratification, when the bottom temperature is higher than the surface temperature, the lake mixes very slowly (Figure 3). This situation is possible in lakes with high transparency and small depth (for example, 5 m), because the incoming solar radiation heats the bottom of the water body. For such cases of unstable density stratification, a bulk scheme of instantaneous mixing is introduced (the results using this scheme are presented in Figure 4).

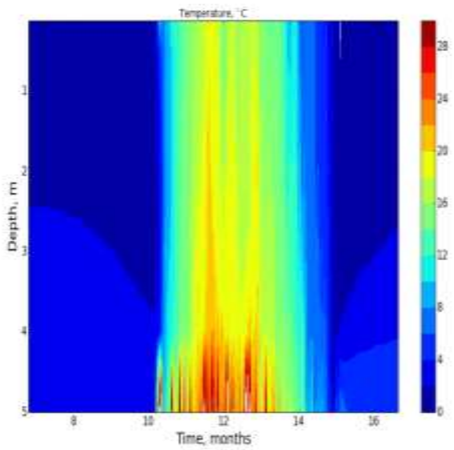

Figure 3. Time-depth distribution of temperature in a 5 m-deep water reservoir during the annual cycle without convective mixing scheme.

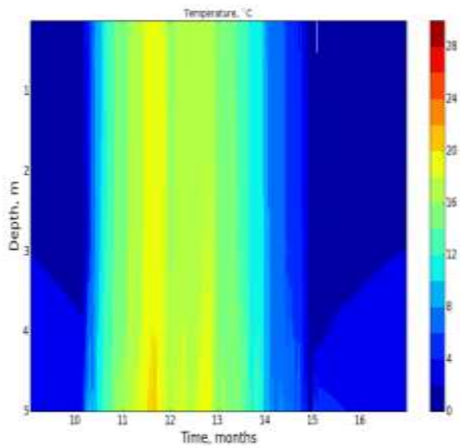

Figure 4. Time-depth distribution of temperature in a 5 m-deep water reservoir during the annual cycle with convective mixing scheme.

3. Validation of lake surface temperature from INMCM4 model vs. measurement data

The surface temperatures of lakes calculated by the LAKE parameterization with the atmospheric forcing from the INMCM4 model were validated vs. measurement data from the database https://portal.lternet.edu/nis/mapbrowse?packageid=knb-lter-ntl.10001.3. A comparison was carried out for lakes located in different climates and on different continents. From Table 1 it follows that the model satisfactorily reproduces the averaged temperature of the surface water with the meteorological forcing of the climate model.

Table 1. Modeled and observed mean surface temperatures of large lakes.

Lake, country	The 5-year (1980-1985) averaged summer surface temperature, modelled, °C.	The 15-year (1986-2000) averaged summer satellite-derived surface temperature, °C.
Huron, Canada	19.2	18.52
Victoria, Tansania-Kenya-Uganda	25.25	23.84
Baikal, Russia	14.83	12.74
Ladoga, Russia	15.49	14.61

The modified model INMCM4 was used to conduct climate simulations for the second half of the XX century. The difference of the monthly-averaged surface temperature and heat fluxes between the old lake parameterization of INMCM4 and the new parameterization (LAKE) was analyzed (Figures 5-8). A conspicuous feature seen in Figures 5-8 is the phase shift in the surface temperature and fluxes between the two model runs, with a warmer lake surface and larger heat fluxes during the late summer and autumn, when using the LAKE model. Due to the fact that the depth of daily active layer of the Earth, the heat-storage, is about 20 centimeters, while for a lake daily active layer, as a rule, is equal to mixed layer and is in the order of a few meters or more. The albedo of the land is equal to 0.1-0.3, and for a lake is 0.06. Thus lakes are more energy-intensive reservoirs with greater absorption of shortwave radiation. For this reason, the surface temperature of a reservoir, as compared to the land temperature, grows slower in summer and cooled slower in autumn. This explains differences in received flows of sensible and latent heat between the two parametrizations of inland waters. It corresponds well to the same well-known differences between the real lakes and the land surface due to deeper heat transfer in the lakes compared to that in soil.

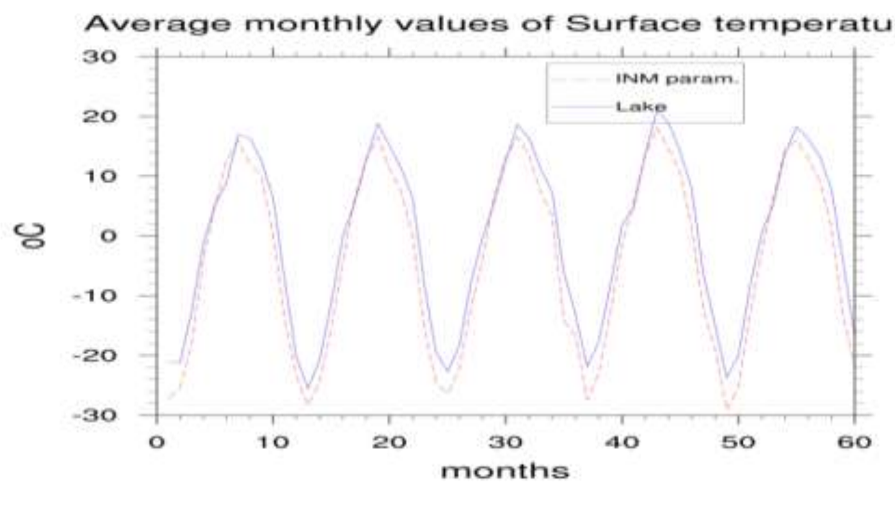

Figure 5. Monthly-averaged surface temperature for Lake Baikal, 60 months from 1980 to 1985.

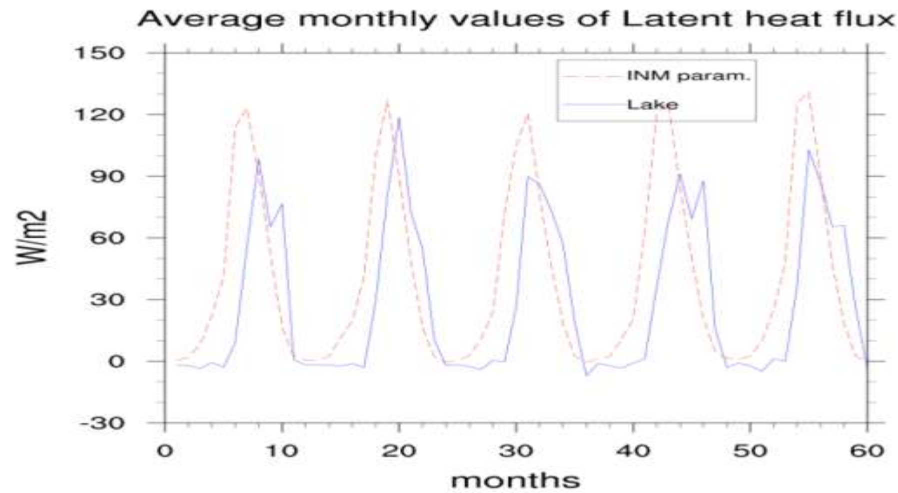

Figure 6. Monthly-averaged surface latent heat fluxes for Lake Baikal, 60 months from 1980 to 1985.

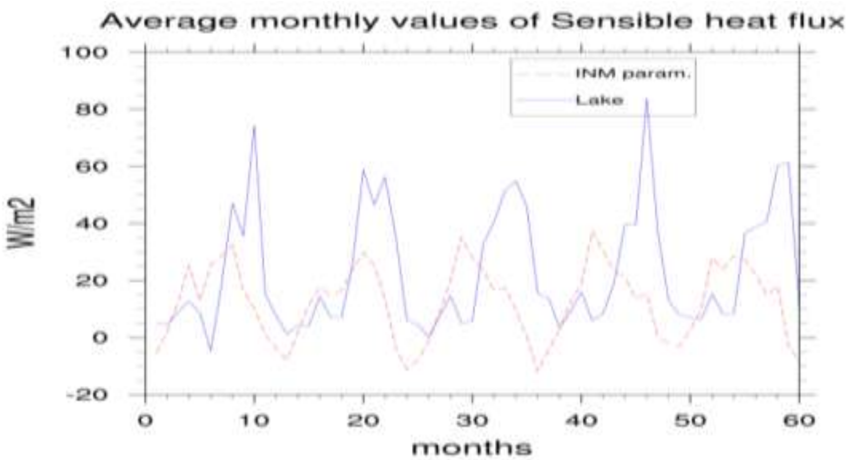

Figure 7. Monthly-averaged surface sensible heat fluxes for Lake Baikal, 60 months from 1980 to 1985.

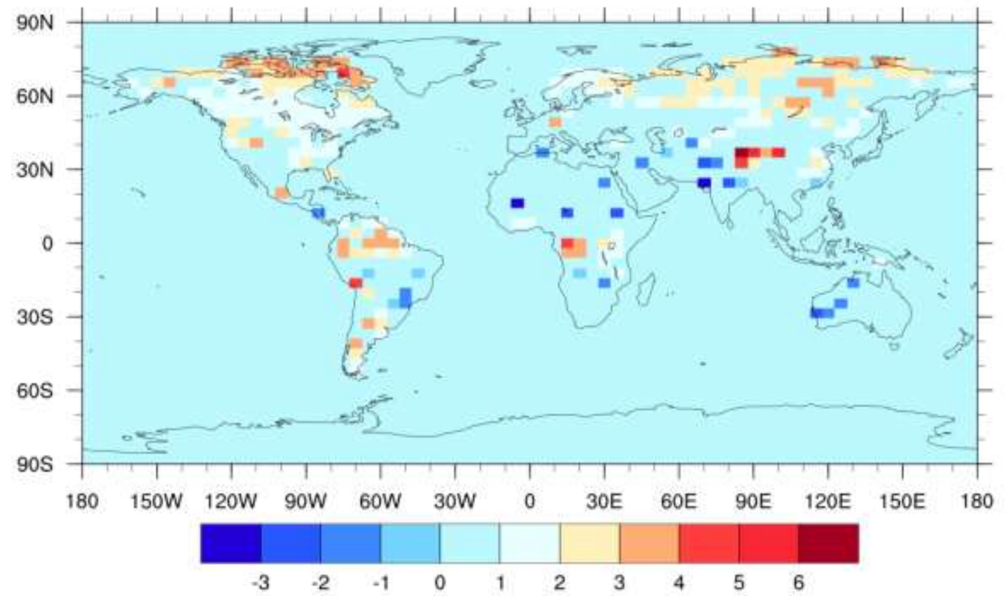

Figure 8. Difference between averaged annual temperatures of water bodies calculated with new and old lake parameterizations, 1981.

From this analysis it follows that a significant difference in the surface temperature between the two parameterizations holds after the temporal averaging. It is noteworthy that the use of the new lake parameterization decreases the surface water temperature in the desert areas, and increases in all the others. One of the likely causes of these differences is the soil type used in the climate model for the respective areas.

Acknowledgments
Work on the new digital maps, preparation of the necessary observational data and global distribution of lakes, the inclusion of new physics in the lake model, validated by measurement data, as well as work on the integration of the models in the first phase (without a return interaction) was to RSF support projects № 16-19-10257. Work on the integration of the models in the second phase (reacting with reverse), experimenting with numerical climate model for the provision of computational resources INM was RSF support projects № 14-27-00126 in INM RAS.

References

[1] Dutra E *et al* 2010 An offline study of the impact of lakes on the performance of the ECMWF surface scheme *Boreal Environment Research* **15** 100–112
[2] Martynov A *et al* 2012 Interactive lakes in the Canadian Regional Climate Model, version 5: the role of lakes in the regional climate of North America *Tellus* A **64** Available at: **http://www.tellusa.net/index.php/tellusa/article/view/16226/xml**
[3] Eerola K *et al* 2014 Impact of partly ice-free Lake Ladoga on temperature and cloudiness in an anticyclonic winter situation – a case study using a limited area model *Tellus* A **66** Available at: http://www.tellusa.net/index.php/tellusa/article/view/23929/xml
[4] Mironov D *et al* 2010 Implementation of the lake parameterisation scheme FLake into the numerical weather prediction model COSMO *Boreal Environment Research* **15**(2) 218–230
[5] Subin Z M *et al* 2012 Boreal lakes moderate seasonal and diurnal temperature variation and perturb atmospheric circulation: analyses in the Community Earth System Model 1 (CESM1) *Tellus* A **64** Available at: **http://www.tellusa.net/index.php/tellusa/article/view/15639/xml**

[6] Rontu L *et al* 2012 Data assimilation and parametrisation of lakes in HIRLAM *Tellus* A **64** Available at: **http://www.tellusa.net/index.php/tellusa/article/view/17611/xml**
[7] Volodin E M Dianskii N A and Gusev A V 2010 Simulating present-day climate with the INMCM4.0 coupled model of the atmospheric and oceanic general circulations *Izvestiya Atmospheric and Oceanic Physics* **46**(4) 414–431 Available at: **http://link.springer.com/10.1134/S000143381004002X**
[8] Stepanenko V M *et al* 2011 Numerical modeling of methane emissions from lakes in the permafrost zone *Izvestiya Atmospheric and Oceanic Physics* **47**(2) 252–264 Available at: **http://link.springer.com/10.1134/S0001433811020113**.
[9] Kourzeneva E Asensio H Martin E and Faroux S 2012 Global gridded dataset of lake coverage and lake depth for use in numerical weather prediction and climate modeling *Tellus* A **64** 15640 DOI: 10.3402/tellusa.v64i0.15640
[10] Henderson-Sellers B 1985 New formulation of eddy diffusion thermocline models *Applied Mathematical Modelling* **9**(6) 441–446 Available at: http://www.sciencedirect.com/science/article/pii/0307904X85901106
[11] Slater A G and Lawrence D M 2013 Diagnosing Present and Future Permafrost from Climate *Models Journal of Climate* **26**(15) 5608–5623
[12] Volodin E M Lykossov V N 1998 Parameterization of heat and moisture processes in soil-vegetation system 1 Description and calculations using local observational data *Izvestia Atmospheric and Oceanic Physics* **34**(4) 453–465
[13] Machul'skaya E E and Lykosov V N 2009 Mathematical modeling of the atmosphere-cryolitic zone interaction *Izvestiya Atmospheric and Oceanic Physics* **45**(6) 687–703 Available at: **http://link.springer.com/10.1134/S0001433809060024**
[14] Zilitinkevich S S *et al* 2013 A Hierarchy of Energy- and Flux-Budget (EFB) Turbulence Closure Models for Stably-Stratified Geophysical Flows *Boundary-Layer Meteorology* **146**(3) 341–373 Available at: **http://link.springer.com/10.1007/s10546-012-9768-8**
[15] Tranvik L J *et al* 2009 Lakes and reservoirs as regulators of carbon cycling and climate *Limnol. Oceanogr.* **54**(6) 2298–314
[16] Kessler M A, Plug L J and Walter Anthony K M 2012 Simulating the decadal- to millennial-scale dynamics of morphology and sequestered carbon mobilization of two thermokarst lakes in NW *Alaska Journal of Geophysical Research: Biogeosciences* **117**(G2) Available at: **http://doi.wiley.com/10.1029/2011JG001796**
[17] Tan Z Zhuang Q and Walter A K 2015 Modeling methane emissions from arctic lakes: Model development and site-level study *Journal of Advances in Modeling Earth Systems* 459–483 Available at: **http://doi.wiley.com/10.1002/2014MS000344**
[18] Stepanenko V, Mammarella I, Ojala A, Miettinen H, Lykosov V and Vesala T 2016 LAKE 2.0: a model for temperature, methane, carbon dioxide and oxygen dynamics in lakes *Geosci. Model Dev.* **9** 1977-2006 doi:10.5194/gmd-9-1977-2016
[19] *IPCC 2013 Climate change* 2013 (New York: Cambridge University Press) Available at: **http://www.climatechange2013.org/**
[20] Wilson M F and Henderson-Sellers A 1985 A global archive of land cover and soils data for use in general circulation climate models *J. Clim.* **5** 119–143
[21] Goudsmit G-H 2002 Application of $K-\varepsilon$ turbulence models to enclosed basins: The role of internal seiches *J. Geophys. Res.* **107** 3230 doi:10.1029/2001JC000954