Past and future lake ice covers of the Berlin-Brandenburg area

Juliane Bernhardt [1]*, Georgiy Kirillin[1], Christof Engelhardt[1] and Jörg Matschullat[2]

[1] *Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany*
[2] *Technical University Bergakademie Freiberg, Institute for Mineralogy, Brennhausgasse 14, 09599 Freiberg, Germany*

Corresponding author, e-mail bernhardt@igb-berlin.de

ABSTRACT
Ice covers of Brandenburg lakes have been studied with respect to climate variability and change with the help of a one-dimensional physical lake model FLake, which uses time series of meteorological parameters and lake specific parameters as input data.
The model is able to reconstruct the observed past ice phenology (number of ice days and ice start and end dates) of two lakes in the Berlin-Brandenburg area (Lake Müggelsee and Lake Stechlin) very well and with higher accuracy than state-of-the-art linear regression models.
The calibrated and validated model was used to investigate the past and future changes in ice cover timing, intensity and duration of a representative set of Berlin-Brandenburg lakes. For eight lakes covering the range of mean depths and trophic states representative for the region the model predicts its ice phenology until 2100 based on measured meteorology data from the Potsdam station (1947-2007) and simulated meteorology (1961-2100) derived from three regional climate model scenarios (GLOWA, RCAO, WettReg).
Observation and model results showed that deeper lakes had more ice-free winters than shallow lakes. Furthermore, the duration of the ice covered period of shallow, polymictic and turbid lakes was longer than that of deep, dimictic and clear lakes. Thus, shallow and turbid lakes had higher numbers of days per winter covered with ice than deep and clear lakes. Furthermore, mean dates of ice cover formation and break-up of deep and clear lakes are usually later than of shallow and turbid lakes.
Trends with time and increasing temperature of later ice start dates and earlier ice end dates, shortening in ice duration and increasing ice free winters were determined for Berlin-Brandenburg lakes for the past and future climate. For the near future (ca. since 2060) deep and clear Berlin-Brandenburg lakes were predicted to become completely ice free.
FLake is a good tool for forecasting lake ice phenology for lakes differing in morphology and trophic state. This is relevant to predict climate change effects on lake ecosystems and freshwater quality. Decreasing lake ice coverage with further climate warming will affect lakes temperature and oxygen, nutrient and light levels of freshwater bodies, thus it is likely to change species composition, timing and abundance from low to high trophic levels (lake ecosystems).

KEYWORDS
Past and future lake ice, freezing, melting, freshwater lake model FLake, climate.

INTRODUCTION

Climate warming took place during the last decades of the 20th century, and the increase in northern hemispheric temperatures continues, being most pronounced in spring (IPPC 2001). Warmer air temperatures affect water body's temperature, ice cover and lake ecology. Timing of initial ice cover freezing and final thawing and the duration of an ice covered period are referred to as ice phenology. Ice phenology parameters have been widely used for various climate studies (Futter, 2003; Kouraev *et al.*, 2008; Williams *et al.*, 2004) as they are good indicators of regional and large-scale climate variability and change.

Timing, presence and duration of lake ice covers are strongly related to local weather conditions, especially air temperature and wind speed, as they are closely linked to water temperature and stratification of lakes. Snow-depth on lake ice also plays an important role in determining ice break-up dates, but observations on this are rarely available. Other factors that determine ice covers on lakes are exposure to wind, lake volume, lake bottom morphology, mean depth and mean surface area (Adrian and Hintze, 2000; Gao and Stefan, 1999; Kouraev *et al.*, 2008; Livingstone, 1997, 2008; Williams *et al.*, 2004).

Lake ice phenology, ice thickness and snow cover affect substantially chemical and physical lake characteristics and the functioning of the ecosystems in lakes. E.g. timing and magnitude of algal blooms, composition of plankton and fish communities are influenced by lake ice characteristics (Adrian *et al.*, 1999, 2006; Assel and Robertson, 1995; Kalff, 2002; Kouraev *et al.*, 2008). Therefore, changes in ice phenology may have potential effects on lake's food webs and water quality.

Climate change studies based on ice phenology have been conducted for many North American lakes but for a few European lakes only (Magnuson *et al.*, 2000; Liston and Hall, 1995; Ménard *et al.*, 2002; Stefan and Fang, 1997; Varvus *et al.*, 1996; Futter, 2003; Livingstone, 2008; Jeffries *et al.*, 2005; Gao and Stefan, 1999; George, 2007; Shuter *et al.*, 1983; Williams *et al.*, 2004). The sensitivity of ice phenology to climate variability and change has been investigated using observation data from ground and remote sensing and simulation data from computer models and regression models (Jeffries *et al.*, 2005). Many long time series of field observations, taken at coastal stations and during field trips, are available for different regions of North America (e.g., Liston and Hall, 1995; Ménard *et al.*, 2002; Stefan and Fang, 1997; Varvus *et al.*, 1996). Since the 1970s, observations by aerial surveys or satellites provide passive microwave images to study lake ice phenology (Kouraev *et al.*, 2008, Leppäranta and Wang, 2008). Single and multiple variable regression analyses were used to develop regression models that need observed ice data and few correlated input data to predict ice phenology and ice thickness (Gao and Stefan, 1999; George, 2007; Williams *et al.*, 2004). A few physical models have been developed to simulate lake ice (e.g., Bilello, 1964; Palecki and Barry, 1986; Livingstone, 1997; Heron and Woo, 1994; Liston and Hall, 1995; Stefan and Fang, 1997; Varvus *et al.*, 1996) that are applicable for a broader range of lakes and more accurate in forecasting lake ice than regression models.

This study aims at reconstructing Berlin and Brandenburg lake ice covers of the past since 1947, particularly for lakes with no observations. The reliability of FLake for forecasting ice phenology of different lake types is tested. Further purposes are detecting past and future trends in regional lake ice phenology, and quantifying responses of the ice regime in lakes with different morphometry and trophy due to climate variability and change.

METHODS

Sites

Lakes in the Berlin-Brandenburg area are lowland lakes that range from deep and clear lakes with big surface areas to shallow and turbid lakes with small surfaces. Of this region, two well studied lakes with regard to lake ice coverage, namely Lake Müggelsee and Lake Stechlin, were used for models calibration and validation.

Lake Müggelsee is a shallow, eutrophic and polymictic lake in the southeast of Berlin, Germany (52´27 N, 13´39 E). It has a mean depth of 4.8 m, a maximum depth of 8.9 m and covers an area of 7.6 km^2 (Fig. 1, Table 1).

Table 1. Lake morphology and water quality parameters of the eight Berlin and Brandenburg lakes (Mischke and Nixdorf, 2008)

d = class width	Lake morphology					Water quality	
Lake class mean depth in m	**Mean depth in m**	**Maxi-mum depth in m**	**Lake area in ha**	**Mixis**	**Lakes**	**Mean Secchi depth in m**	**Mean extinction coefficient**
11 ≥ d < 25	24.2	69.5	412.38	stratified	Lake Stechlin (1)	8.5	0.20
	19.3	36.0	105.97	stratified	Lake Sacrow (2)	1.4	1.26
5 ≥ d < 11	7.1	18.0	162.00	stratified	Lake Nehmitz (3)	6.6	0.27
	5.5	9.8	1482.71	stratified	Lake Wannsee (4)	0.8	2.27
2 ≥ d < 5	4.8	8.9	764.61	polymictic	Lake Müggelsee (5)	1.8	0.80
	2.8	6.3	507.43	polymictic	Lake Selchow (6)	0.4	4.00
0 > d < 2	1.7	4.8	237.21	polymictic	Lake Schwerin (7)	0.6	3.09
	1.5	4.5	96.10	polymictic	Lake Grössin (8)	0.3	5.31

Figure 1. Location of the eight lakes in Berlin and Brandenburg

Full mixing of the lake body often takes place because of its shallowness and relatively big surface area. The lake is flushed by the River Spree and had a mean water retention time of 6-8 weeks. The surrounding topography is flat and the lake basin is oriented from east to west; hence the lake is highly exposed to the prevailing winds from the southwest (Driescher *et al.*, 1993).

Lake Stechlin, situated in the Baltic Lake District in NE Germany (53´09 N, 13´02 E), about 100 km north of Berlin, has a surface area of 4.1 km^2. Maximum and mean depths are 69.5 and 24.2 m, respectively (Fig. 1, Table 1). Relatively large depths and small horizontal dimensions cause the dimictic character of the lake. The water level of the oligotrophic lake is regulated by ground water inflow, precipitation (about 590 mm a^{-1}) and evaporation, and temporal runoff through the surrounding sand layers (Casper, 1985; Koschel and Adams, 2003). Relatively weak, predominately westerly winds with average speeds of 2–3 m s^{-1} characterise the area.

For simulations with the lake model FLake eight Berlin and Brandenburg lakes were chosen in respect to their mean lake depth and turbidity, representing the diversity of lakes in this region (Fig. 1). Four lake depth classes were formed ($0 > d < 2$ m, $2 \geq d < 5$ m, $5 \geq d < 11$ m and $11 \geq d < 25$ m), with one turbid and one relatively clear lake in each lake class (Table 1).

The FLake model

The physical lake model FLake (Mironov, 2008) is driven only by few external variables. Lake-specific variables are lake depth, optical characteristics of lake water, temperature at the bottom of the thermally active layer of bottom sediments, and the depth of this layer. The model requires time series of the five meteorological parameters solar radiation, air temperature, air humidity, wind speed and cloudiness as input. The model was run with a daily time step. From these simulation results (daily ice thickness), the number of ice days per winter, freeze-up and break-up dates and the duration of the ice covered period have been calculated. For simplicity, only the findings of the ice phenology parameter "number of ice days per winter" (*nd*) are shown in the results and discussion section.

Past meteorology and future scenarios

Observed meteorological data from 1947 to 2007 have been used from the Potsdam station (WMO station ID: 10379) of the German Weather Service (DWD). The station's coordinates are 52°23'N, and 13°04'E, and it is situated at an altitude of 81 m a.s.l. on Telegrafenberg. The lake model FLake was driven with measured daily average meteorological data from November the 1st 1947 to October the 31st 2007 (60 hydrological years) to model the ice phenology of the past. Accessible data from DWD were the daily sum of solar radiation (J cm^{-2}), the daily mean air temperature measured in 2 m height (°C), the daily relative air humidity (%) and the daily mean wind speed (Bft). Mean daily air temperature at the Potsdam station was 9°C (± 7.8°C) in the period from 1947 to 2007.

To simulate future ice phenology, and thus the response to the expected climatic changes, meteorology data from three regional climate scenarios (GLOWA, RCAO MPI B2 and WettReg) were used. The first two regional climate scenarios are both based on the same driving global climate model ECHAM 4 (OPYC3-T24) of the Max Planck Institute Hamburg for Meteorology (Roeckner *et al.*, 1996) with the SRES emission scenario B2, but on two different regionalisation procedures and time coverages. The first one is based on the statistical downscaling procedure STAR (Werner and Gerstengarbe, 1997) and run for the period 2001-2055, and the second one is based on the regional climate model RCA (Rummukainen *et al.*, 2001) and run for the time span 2071-2100. In the third scenario, the newer global climate model ECHAM 5 with the more extreme SRES emission scenario A1B (IPCC, 2007) provided the boundary conditions for the regional climate model WettReg (Enke *et al.*, 2005a; Enke *et al.*, 2005b).

In the past, mean annual air temperatures showed an increasing trend of ca. 1°C in 60 years (or 0.017°C per year). The GLOWA regional climate scenario for 2001 to 2055 is based on the prescribed linear temperature trend of a 1.4°C temperature increase per 50 years or a 0.0257°C temperature increase per year. The air temperature increase in the RCAO MPIB2 scenario for 2071 to 2100 is also based on the ECHAM/OPYC3 results of the global circulation modeling and roughly amounts to a 0.03°C temperature increase per year. The statistical model WettReg, based on large scale weather patterns, comprises a temperature increase of approximately 3°C for the period 1961-2100 (or 0.02°C per year) for the south and east of Germany.

Models calibration and validation

As mentioned above, there are only two long time series of lake ice phenology available for the Berlin and Brandenburg area. Calibration and validation of the FLake model, and comparison to the state-of-the-art linear regression models (Gao and Stefan, 1999; George, 2007; Shuter *et al.*, 1983; Williams *et al.*, 2004) were performed at these data sets from Lake Müggelsee and Lake Stechlin. For both lakes, ice observations are available without gaps for the time period from 1961 to 2007 (Fig. 2, grey bars). The calibration period for Lake Müggelsee was from 1976 to 1991 and for Lake Stechlin from 1961 to 1981, and the validation period for Lake Müggelsee was from 1991 to 2007 and for Lake Stechlin from 1981 to 2002.

The model calibration was performed by adjusting lake-specific input parameters (Table 2) in order to obtain the best fit of model results with the observed ice data. Lake parameters (Table 2, dark grey) that fitted best for Lake Müggelsee and Lake Stechlin during the calibration periods were adapted to further selected Berlin and Brandenburg lakes. After that, the model was validated on data from the chosen validation period.

Table 2. Lake specific input parameters to FLake sorted from deep to shallow Berlin and Brandenburg lakes

Lake name	Latitude	Mean extinction coefficient (Apr.-Oct.)	Mean lake depth in m	Ice water heat flux in W m^{-2}	Depth thermal active layer bottom sediment in m	Temperature outer edge bottom sediment in °C	Albedo lake ice cover
Lake Stechlin	53°09'	0.20	24.16	3	3	7	0.1
Lake Sacrow	52°27'	1.26	19.30	3	3	7	0.1
Lake Nehmitz	53°08'	0.27	7.14	5	3	7	0.1
Lake Wannsee	52°27'	2.27	5.50	5	3	7	0.1
Lake Müggelsee	52°27'	0.80	4.80	5	3	7	0.1
Lake Selchow	52°13'	4.00	2.82	5	3	7	0.1
Lake Schwerin	52°12'	3.09	1.68	5	3	7	0.1
Lake Grössin	52°15'	5.31	1.47	5	3	7	0.1

In order to estimate coefficients in the regression models the lake ice phenology observations from both lakes were used. The 11 linear regression models were constructed each including one lake morphological variable (mean lake depth or mean lake area), and one meteorological variable (annual mean air temperature from Potsdam station (DWD) or winter North Atlantic Oscillation Index (mean from Dec-Mar)) (Hurrel, 1995). Table 3 shows selected linear regression equations for predicting the number of ice days (*nd*) and the ice start date (*sd*). The equations obtained with the data from the calibration period were tested on the validation period.
Finally, ice observations, regression and lake model results were compared for Lake Müggelsee and Lake Stechlin in the period from 1961 to 2007 (Fig. 2).

Past and future simulations
Daily lake ice thicknesses of eight Berlin and Brandenburg lakes were modelled for the past from 1947 to 2007 and for the future till 2100. For the eight lakes annual ice phenology data and its means of the modelled past and future time periods were examined (Figs. 3-6). Trends with 1°C rising air temperature were calculated for the past and future ice phenology of Lake Müggelsee and Lake Stechlin (Figs. 7-9).

RESULTS AND DISCUSSION

Calibration and validation

During 1961-2007 shallow and turbid Lake Müggelsee had more winters covered with ice than deep and clear Lake Stechlin. Furthermore, the ice-covered periods of Lake Müggelsee were longer, and the number of ice days per winter was higher than for Lake Stechlin (Fig. 2, grey bars).

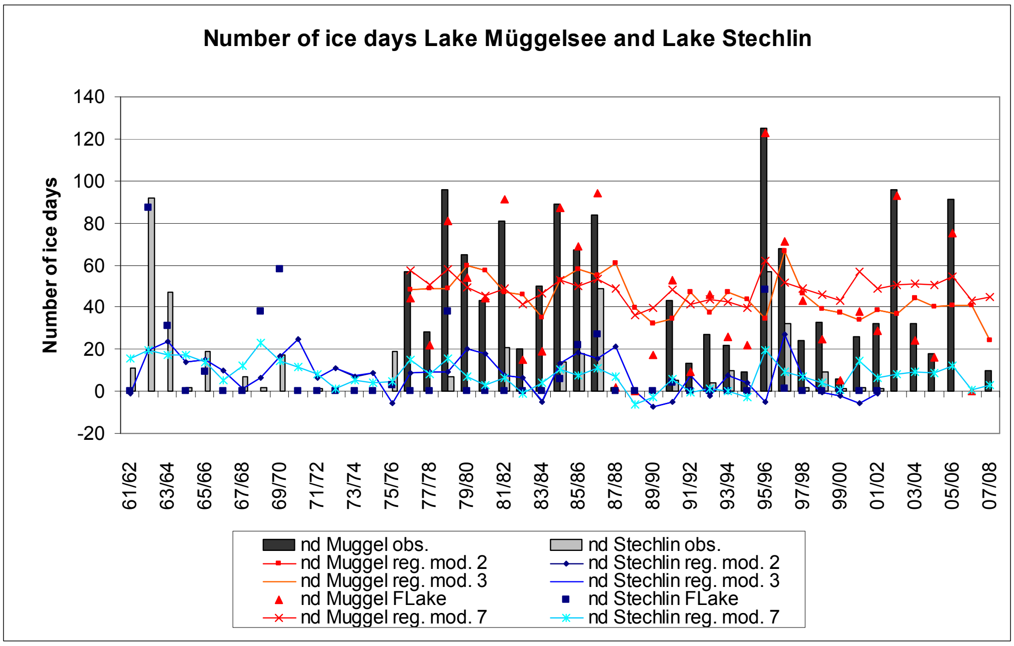

Figure 2. Numbers of ice days for Lake Müggelsee and Lake Stechlin since 1961. Bars show the observed ice data, lines are the numbers of ice days predicted by regression models (Eq. 2, 3, 7, 8), dots mark the numbers of ice days modelled by the FLake

The FLake performed well in predicting lake ice phenology for Lake Müggelsee and Lake Stechlin, with significant linear correlation coefficients between observed and modelled ice phenology parameters for both calibration and validation period. The errors between observed and simulated ice parameters of the calibration and the validation period are in the same order of magnitude for both lakes. The mean absolute error (MAE) of the number of ice days per winter (*nd*) was between 6.4 and 9.2 days and of the timing of ice break-up (*ed*) between 5.3 and 9.8 days. The MAE of the timing of lake ice freeze-up (*sd*) was with from 6.7 to 18.2 days not as good as for the other two ice phenology parameters. Similar errors are found by Ménard *et al.* (2002). Ice-covered and ice-free winters were well simulated for both lakes. FLake slightly overestimated the number of ice days for Lake Müggelsee and slightly underestimated (yet, in some cases, strongly overestimated) *nd* for Lake Stechlin. For Lake Stechlin strong overestimation of ice days occurred when air temperatures in this year have been low, thus a high number of ice days have been modelled by FLake, but no ice cover or only a few days ice have been observed (Fig. 2, dots).

As a reference, several linear regression models were developed predicting lake ice parameters from meteorology and lake morphology variables. The most important climate parameters for predicting lake ice phenology with regression models were annual mean air temperature and North-Atlantic-Oscillation-Index (NAO-I). The strongest correlations between lake specific parameters and lake ice phenology were found for mean lake depth and mean lake area, which is in agreement with the findings of e.g., Gao and Stefan (1999), Livingstone and Dokulil (2001), Shuter *et al.* (1983) and Williams *et al.* (2004). The regression models constructed here are shown in Table 3.

For the calibration period, two regression equations were significant ($p < 0.05$) for predicting the number of ice days (Eqs. 2 and 3, Fig. 2), three regression equations for the ice start dates (Eqs. 4, 5 and 6) and none of the equations for ice end dates for Lake Müggelsee and Lake Stechlin. For the validation period, the regression models 2, 3, 4, 5 and 6 which used the annual mean air temperature to predict *nd* and *sd*, were insignificant. Regression models predicting *nd* (Eqs. 7 and 8) from the winter NAO-I were significant for both calibration and validation period (Fig. 2). Results of models 2 and 3, as well as those of models 7 and 8, are identical because they use nearly the same input except for depth and area (Table 3, Fig.2). Number of ice days for both lakes predicted by regression models 2 and 7 are shown in Figure 2 (lines).

Table 3. Linear regression models for predicting ice phenology parameters

Linear regression model	Equation number
nd = 89.952 - 7.201* Temp N_O	(Eq. 1)
nd = 153.944 -10.817 * Temp N_O -2.045 * mean depth	(Eq. 2)
nd = 58.309 -10.817 * Temp N_O + 11.218 * mean area	(Eq. 3)
sd = 256.569 + 14.728 * Temp N_O	(Eq. 4)
sd = 210.291 + 17.343 * Temp N_O + 1.479 * mean depth	(Eq. 5)
sd = 279.453 + 17.343 * Temp N_O -8.113 * mean area	(Eq. 6)
nd = 61.644 -2.910 * NAOI (DJFM) -2.183 * mean depth	(Eq. 7)
nd = -40.426 -2.910 * NAOI (DJFM) + 11.973 * mean area	(Eq. 8)

The deterministic model FLake predicted lake ice phenology much better than linear regression models (Fig. 2). The ice data modelled by FLake reflect the high inter-annual variability typical for observed ice phenology (Futter, 2003). In contrast, regression model results reproduce only mean ice phenology on longer time periods. This agrees with the results of Williams *et al.*, (2004) who stated that the best multiple regression analyses cannot account for the full range of annual variability in the historical records, implying the absence of influential factors from these regression models. Simple or multiple linear regression models can be adopted to gain first knowledge on mean ice phenology of lakes in a distinct region and time window. The predicted data give an overview of ice phenology, if only few input variables are available at a poorer time resolution.

FLake includes more meteorological data with higher temporal resolution than the regression models. Only one meteorological input parameter, the annual mean air temperature or the winter mean NAO-I, was used for the regression models. Five meteorological variables were used with daily resolution to drive FLake. Furthermore, the one-dimensional lake model incorporates more lake specific input data than the regression models. Only mean lake area and mean lake depth were used for the regression models.

Past and future lake ice phenology

FLake was applied to eight different lakes of the Berlin and Brandenburg area for one past period (1947-2007), using observed Potsdam data, and for two future periods (2001-2055; 2071-2100) using simulated data derived from GLOWA-scenarios and RCAO-scenarios. In addition, FLake runs using 20 different simulated WettReg-realisations (1961-2100) were performed only for the lakes Stechlin and Müggelsee providing with minimum and maximum estimates of possible future ice phenology.

Under the same meteorological forcing, the ice characteristics, such as mean number of ice days and percentage of ice covered winters, differed for the eight lakes mostly due to differences in the mean lake depth. The shallower a lake the more days are likely to be covered with ice in each winter (Fig. 3) and the less ice-free winters are likely to occur (Fig. 4).

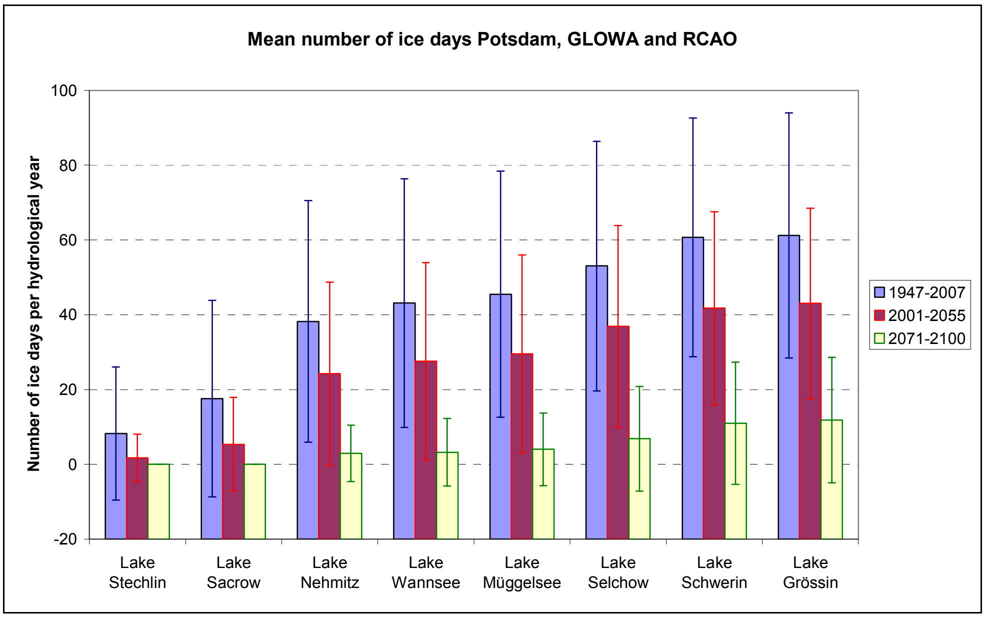

Figure 3. Mean numbers of ice days (± standard deviation) for eight Berlin and Brandenburg lakes for periods 1947-207, 2001-2055 and 2071-2100 modelled by FLake.

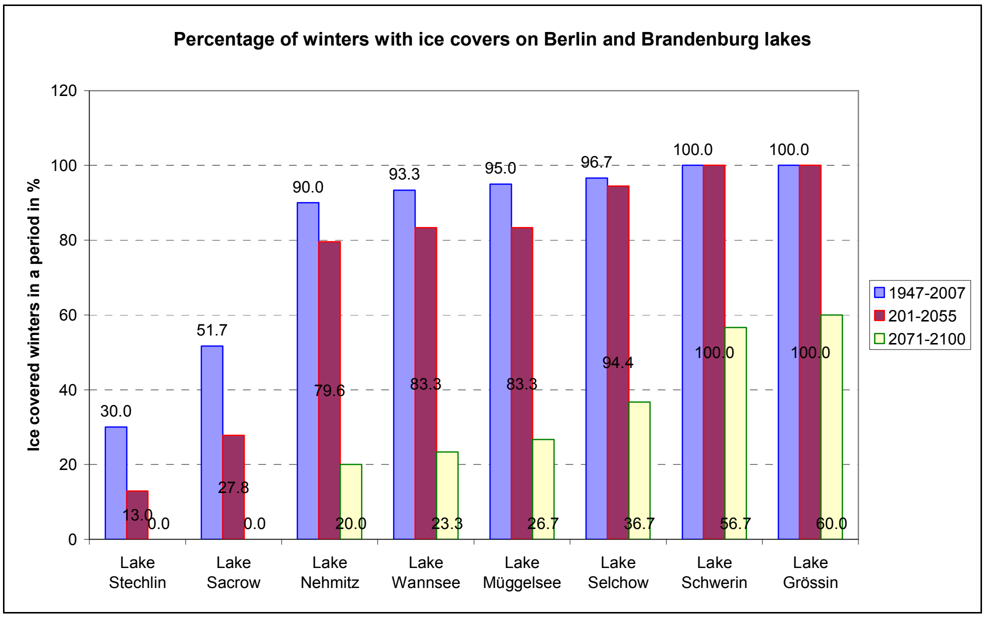

Figure 4. Percentage of ice covered winters for eight Berlin and Brandenburg lakes during 1947-2007 (blue bars), 2001-2055 (red bars) and 2071-2100 (yellow bars), modelled by FLake.

There were significant differences between "number of ice days" means of the modelled time periods, as mean *nd* of the past period (1947-2007) was highest, lower for the closest future scenario from 2001-2055 (GLOWA), finally lowest for the latest future scenario from 2071-2100 (RCAO). The modelled means of *nd* varied in 1947-2007 between 8 and 61 days, in 2001-2055 between 2 and 43 days and in 2071-2100 between 0 and 12 days (Fig. 3). For Lake Müggelsee and Lake Stechlin declining numbers of ice days per winter, modelled using four different scenarios, in the period from 1947 to 2100 are shown in Figs. 8 and 9.

Thus, *nd* decreased with time and increasing air temperature. Trends of *nd* are strongest for the past modelled period and get weaker for the future periods. Thus, modelling results predicted that an increase by 1°C annual mean air temperature caused 16-days (1947-2007) (Fig. 5), 5-days (2001-2055) (Fig. 6) and 2 days (2071-2100) lower numbers of ice days per winter for Lake Müggelsee (Fig. 7). Similar trends in past ice phenology were found e.g. by Magnuson (2008).

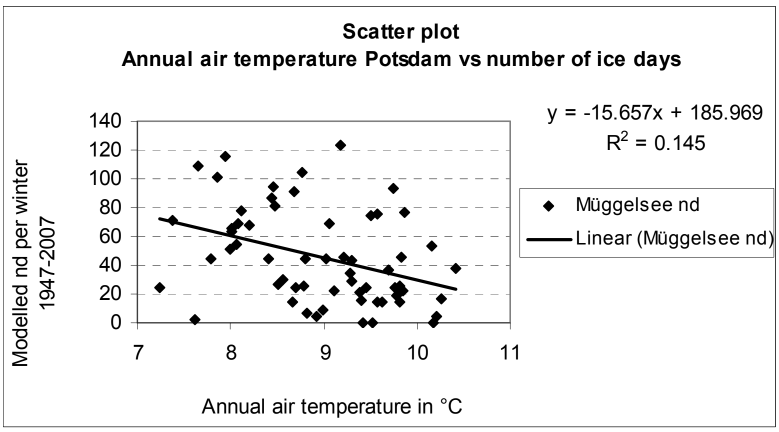

Figure 5. Linear trend of the modelled (FLake) number of ice days (*nd*) for Lake Müggelsee with increasing air temperature 1947-2007

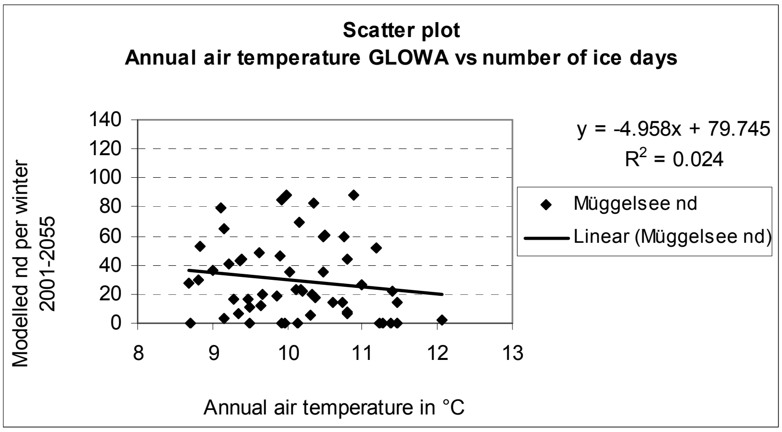

Figure 6. Linear trend of the modelled (FLake) number of ice days (*nd*) for Lake Müggelsee with increasing air temperature 2001-2055

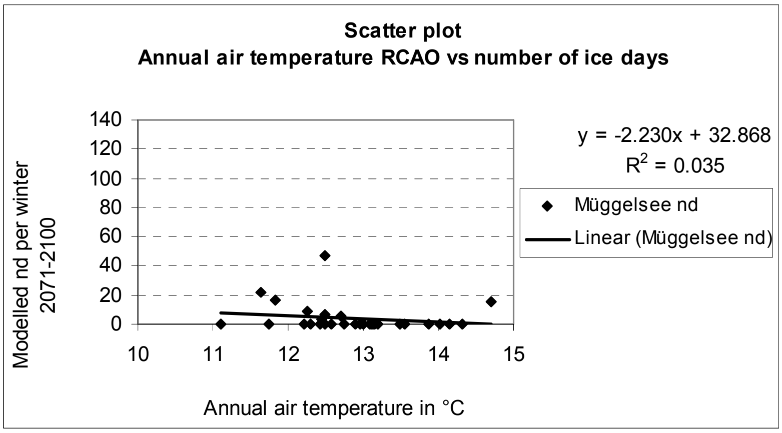

Figure 7. Linear trend of the modelled (FLake) number of ice days (*nd*) for Lake Müggelsee with increasing air temperature 2071-2100

According to FLake-simulations ice-free winters are likely to increase drastically with time and ice covered winters are likely to decrease with increasing mean lake depth (Fig. 4). In the past period 1947-2007 shallow Lake Müggelsee was ice covered 95% of the winters and deep Lake Stechlin 30%. For the future period 2001-2055 (GLOWA-scenario) 83% of the winters are predicted to be ice covered for Lake Müggelsee and 13% for Lake Stechlin. Dramatic reduction in ice cover according to the RCAO-scenario is predicted for the period from 2071-2100 where only 23% of the winters for Lake Müggelsee and no winters for Lake Stechlin are likely to be ice covered (Fig. 4). In the period from 1961-2100 (WettReg) few or no ice-free winters have been modelled for shallow lakes and more ice-free winters than ice-covered winters were simulated for deep lakes (Figs. 8 and 9).

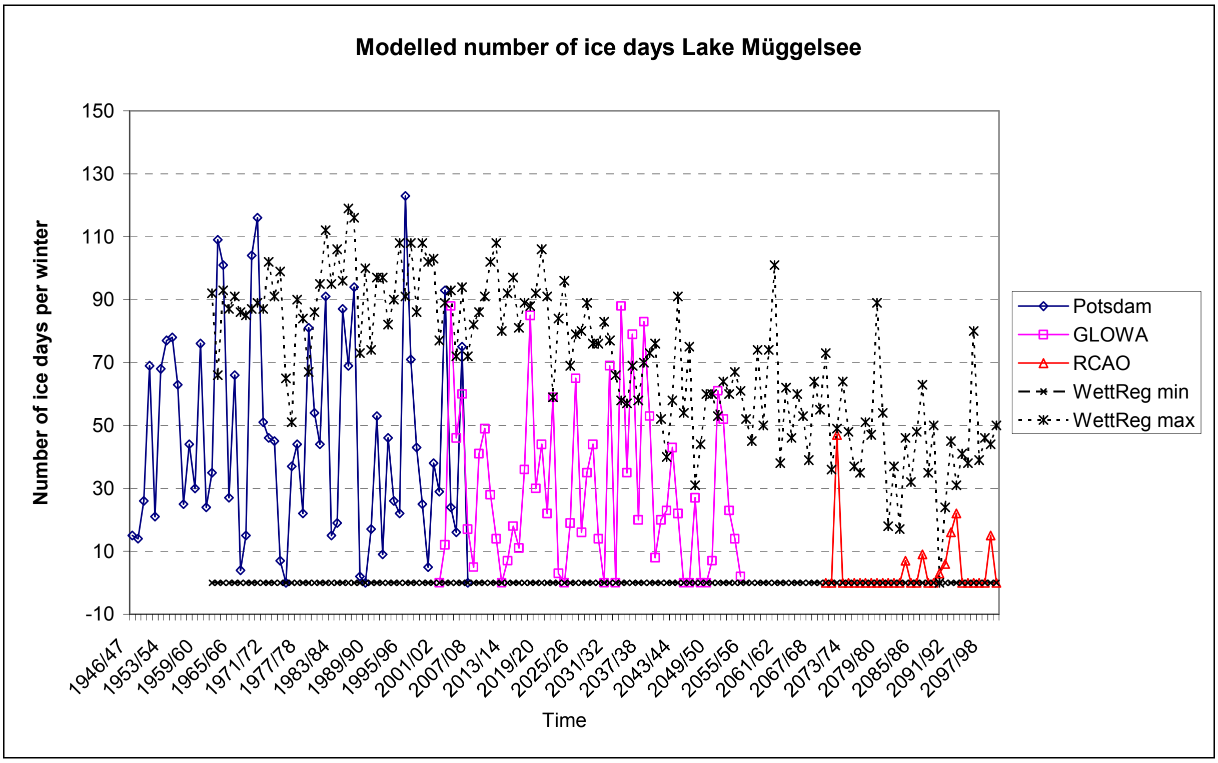

Figure 8. Modelled number of ice days per winter for Lake Müggelsee with 4 different input meteorology time series to FLake (1947-2100): observed data from Potsdam 1947-2007, simulated data derived from the RCMs GLOWA (2001-2055), RCAO (2071-2100) and WettReg (1961-2100). The range of WettReg-realisations is given by the minimum and the maximum numbers of ice days per year

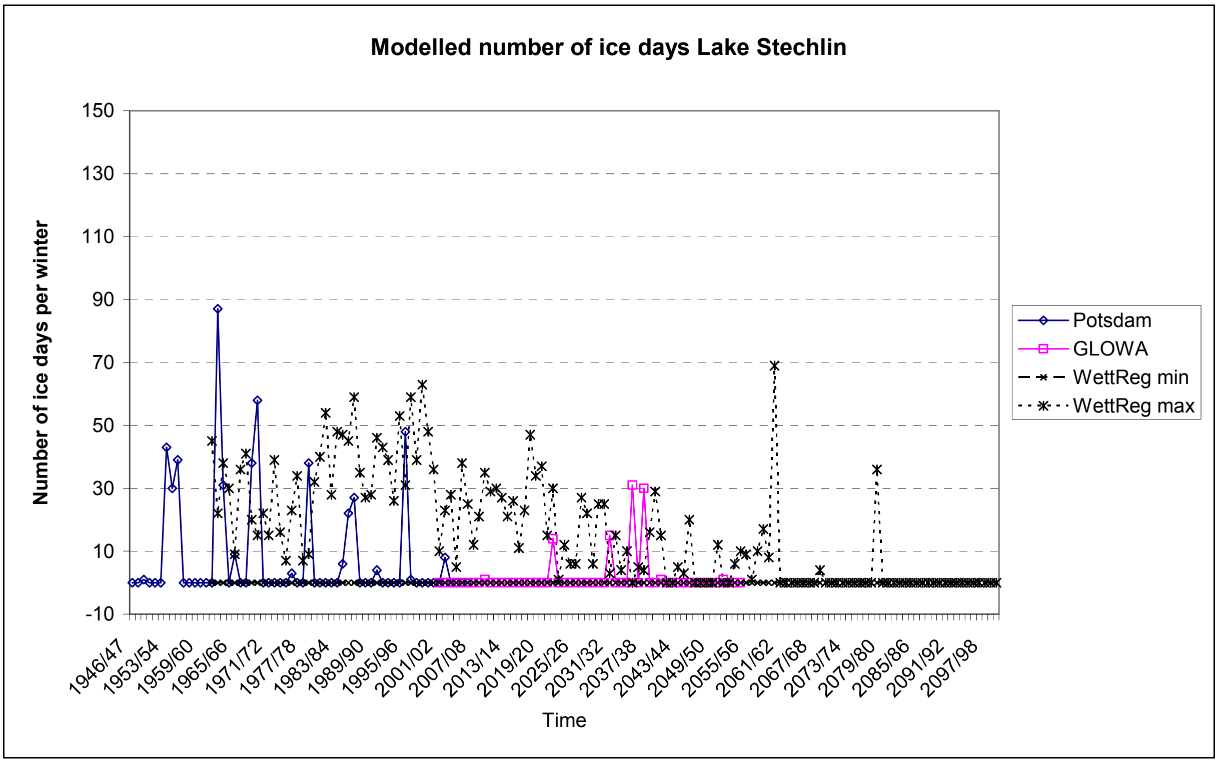

Figure 9. Modelled number of ice days per winter for Lake Stechlin. No ice was modelled for Lake Stechlin using the RCAO input meteorology (further description see Figure 8)

Ice phenology modelling of lakes with a great range of mean lake depth imply that deep, stratified lakes are more strongly affected by climate warming than shallow, polymictic lakes. Duration and intensity of lakes stratification determines lake volume that is directly connected to the water-air-interface (time-dependent). Heat uptake and release of the water body over a year is determined by lake depth, mixed layer depth and duration of stable stratification and mixing. Because the larger lake body can store more and needs longer to release heat (Livingstone, 2008) number of ice covered days of deep lakes was lower than of shallow lakes and mean dates of ice cover formation and break-up were usually later for deep lakes than for shallow lakes. Water body temperature of polymicted shallow lakes is with only a few degrees difference very similar (small time lags) to local air temperature during the year. In contrast, hypolimnion temperature of stratified deep lakes can differ up to 20 degrees to air temperature.
It is likely, that deeper lakes are more strongly affected by the changes in ice phenology than shallow lakes. Thus, a stronger warming trend became more clearly noticeable over the years (climate) for deep lakes than for more shallow lakes that were more affected by current weather conditions.

CONCLUSIONS

The purpose of this study was to model the past ice phenology and to develop future ice scenarios for a variety of freshwater lakes in the Berlin-Brandenburg area. The modelling was aimed at (i) reconstructing the trends in the past ice regime for lakes lacking ice observations, and (ii) estimating the future changes in ice phenology under different climate scenarios, which is important for studying the climate impact on lake ecosystems.
It was shown that the deterministic lake model FLake performs better in reconstructing past lake ice coverage than convenient linear regression models. FLake computes reasonable ice results for shallow, relatively turbid and polymictic, as well for deep, clear and stratified small lakes. The lake model reproduces well the lake ice dynamics, including the high annual variability of ice phenology as well as the intermitted ice coverage per winter. Therefore, the FLake is a reliable tool for studying lake ice phenology and for estimation of the future changes using climate scenarios. Thus, FLake can be applied to model ice covers on lakes all over the world, provided that mean lake depth, water turbidity and meteorological parameters in the lake vicinity are known. Among the major advantages of FLake are: the model is freely available in the internet (open code), is easy to apply by everyone, requires only a few input parameters and is computationally efficient.
Decline in lake ice coverage associated with global climate warming and local air temperature increase could be proved for Berlin and Brandenburg lakes in the past. Past trends of ice reduction are of the same order of magnitude as reported before, (e.g. Magnuson 2008). Further decrease and disappearance of the lake ice coverage in the Berlin and Brandenburg area has been predicted for the future. The overall phenology trends for the past and future climate are: shift to later ice-on and earlier ice-off, with corresponding shortening in the duration of the ice covered period; thinning of ice covers; and increasing number of ice free winters.

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