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Lake ice phenology in Berlin-Brandenburg from 1947–2007: observations and model hindcasts

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Abstract Rising northern hemispheric mean air temperatures reduce the amount of winter lake ice. These changes in lake ice cover must be understood in terms of resulting effects on lake ecosystems. Accurate predictions of lake ice phenology are essential to assess resulting impact. We applied the one-dimensional physical lake model FLake to analyse past variability in ice cover timing, intensity and duration of Berlin-Brandenburg lakes. The observed ice phenology in two lakes in the period 1961–2007 was reconstructed by FLake reasonably well and with higher accuracy than by state-of-the-art linear regression models. Additional modelling results of FLake for 38 Berlin-Brandenburg lakes, observed in the winter of 2008/09, were quite satisfactory and adequately reproduced the effects of varying lake morphology and trophic state. Observations and model results showed that deeper and clearer lakes had more ice-free winters, later ice cover freezing and earlier ice cover thawing dates, resulting in shorter ice-covered periods and fewer ice-covered days than shallow and less clear lakes. The 1947–2007 model hindcasts were implemented using FLake for eight Berlin-Brandenburg lakes without ice phenology observations. Results demonstrated past trends of later ice start and earlier ice end, shorter ice cover duration and an increase in ice-free winters.

Abbreviations

SD	ice start date
ED	ice end date
ND	number of ice days per winter
ID	ice duration
IFW	ice-free winters
Ta	air temperature
NAO-I	North Atlantic Oscillation-Index

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n	number
r	Pearson's correlation coefficient
p	p-value for correlation
MAE	mean absolute error
obs.	observed
reg. mod.	regression model
P	P-value for trends
α	significance level for trends
t*	test value
S_a	standard error

1 Introduction

Climate warming during the last decades of the 20th Century reveals itself in the rise of northern hemispheric temperatures. The most pronounced changes take place in winter (IPCC 2001, 2007) affecting the ice regime of lakes. Lake ice observations over the past 150 years provide a rather high coherence between northern hemisphere air temperatures and lake ice duration (Magnuson et al. 2000a, b).

The timing of initial ice cover freezing and final thawing, and the duration of the ice-covered period are referred to as ice phenology. Related parameters have been widely used for various climate studies, since they are good indicators for regional and large-scale climate variability and change (Johnson and Stefan 2006; Kouraev et al. 2008; Magnuson et al. 2000b; Weyhenmeyer et al. 2011; Williams et al. 2004).

Historical trends in lake and river ice phenology in the northern hemisphere, in Eurasia (e.g., Livingstone 1997, 1999, 2000; Weyhenmeyer et al. 2004) and North America (e.g., Assel and Robertson 1995; Johnson and Stefan 2006; Magnuson 2010; Magnuson et al. 2000a) show evidence of later freezing and earlier break-up, and thus a reduction in ice cover and lower frequency of ice cover due to increasing air temperatures.

The duration of the ice-covered period in the mid-latitudes can vary from a few days to several months, depending on lake characteristics, climate and weather conditions. Timing, presence and duration of lake ice cover are strongly related to local air temperature and wind speed, as they are closely linked to lake temperature and stratification. The physical responses of lakes to meteorological forcing seem to reveal a notable coherence over large spatial scales, indicating that lakes respond not only to local weather, but also to large-scale climate. This could be shown, e.g., in North America with the El Niño/Southern Oscillation and in Eurasia to the North Atlantic Oscillation/Arctic Oscillation (Benson et al. 2000; Blenckner et al. 2007; Bonsal et al. 2006; George 2007; Ghanbari et al. 2009; Jensen et al. 2007; Livingstone 1999, 2000, 2008; Magnuson et al. 2004, 2005). Additional parameters that determine lake ice covers are wind exposure, lake volume, bottom morphology, mean depth and mean surface area (Adrian and Hintze 2000; Gao and Stefan 1999; Jensen et al. 2007; Williams et al. 2004).

The presence of lake ice cover, ice cover duration, timing of ice formation and break up, ice thickness and snow cover on ice can all substantially affect chemical and physical lake characteristics and the functioning of lake ecosystems (Kouraev et al. 2008). Lake ice cover forms a barrier between water and atmosphere, and thus prevents wind mixing and evaporation in addition to reducing heat, mass and gas transport and light penetration (Adrian and Hintze 2000; Kalff 2002). Lake ice cover strongly affects the timing and magnitude of algal blooms as well as species abundance and composition (Adrian et al. 1999; Blenckner et al. 2002). Primary productivity is greatly influenced by the timing and state of a lake's ice cover and overlying snow during the winter. The timing of ice break-up influences the initial growth conditions for diatoms, and thus the timing of spring phytoplankton bloom (Blenckner et al. 2007). Water temperature in late spring directly influences zooplankton growth, such as Daphnia, and the associated timing of the clear-water phase (Straile and Adrian 2000). Warmer water temperatures in spring and summer increase cyanobacteria and cyclopoid copepod biomass in summer (Adrian and Wilhelm 2008; Kardaetz et al. 2008). Effects of lake ice on growth, reproduction and survival of organisms on higher trophic levels are likely, too. Decreases in fish populations with reduction of long term lake ice cover are reported in many studies (Assel and Robertson 1995; Greenbank 1945; Hurst 2007). Less ice on lakes results in more favourable temperature and light conditions, and a higher nutrient supply within the lakes (Adrian and Wilhelm 2008; Blenckner et al. 2002; Kardaetz et al. 2008). Thus, lake productivity is expected to intensify on all trophic levels due to shorter ice-covered periods (Adrian et al. 1999). Changing lake ice phenology caused by increasing air temperatures can also lead to transitions in mixing regimes, e.g., strictly dimictic lakes are likely to become ice-free and thus monomictic, while monomictic lakes are likely to become oligomictic or meromictic (Kirillin 2010; Livingstone 2008).

Climate change studies based on ice phenology have been conducted for many North American lakes (Futter 2003; Jensen et al. 2007; Liston and Hall 1995; Magnuson et al. 2000a; Stefan and Fang 1997; Vavrus et al. 1996), but for only a few European lakes (Adrian and Hintze 2000; George 2007; Leppäranta and Wang 2008; Livingstone and Dokulil 2001). The sensitivity of ice phenology to climate variability and change has been investigated using observations from ground and remote sensing, and simulation data from computer models and regression models (e.g., 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 (northern USA and Canada; e.g., Liston and Hall 1995; Ménard et al. 2002; Stefan and Fang 1997; Vavrus et al. 1996). Since the 1970s, observations by aerial surveys or satellites have provided 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 require observed ice data and a few correlated input data to predict ice phenology and ice thickness (Gao and Stefan 1999; George 2007; Livingstone 1997; Palecki and Barry 1986; Williams et al. 2004). A few physical models have been developed to simulate lake ice (e.g., Heron and Woo 1994; Liston and Hall 1995; Stefan and Fang 1997; Vavrus et al. 1996). These are applicable to a broader range of lakes and are more accurate in forecasting lake ice than regression models.

Here, the reliability of FLake, a one-dimensional lake model (Mironov 2008), to forecast ice phenology in different lake types is being tested. The deterministic lake model FLake and simple state-of-the-art linear regression models have been calibrated and validated using long-term lake ice observations (1961–2007) from Müggelsee and Lake Stechlin, both different in morphology and nutrient content. A comparison of lake ice observations, FLake and regression model results followed for both lakes. To validate the model results, we performed lake ice modelling with FLake for 38 lakes of the Berlin-Brandenburg area with contrasting lake depth and Secchi-depth for the winter 2008/09. The model results were compared with observed lake ice data. In conclusion, we used FLake to model the past lake ice covers of eight selected lakes from 1947–2007 with the aim to quantify the responses of the past ice regime in Berlin-Brandenburg lakes with different morphologies and trophic states to climate change (trends in lake ice phenology).

2 Methods

2.1 Sites and lake-specific model input data

Two well-studied lakes of the Berlin-Brandenburg area with long time-series of ice records (Müggelsee and Lake Stechlin; 1961–2007) were used for model calibration and validation. Both lakes differ in lake depth, extinction coefficient and mixing regime.

Müggelsee (Fig. 1) is a shallow, eutrophic and polymictic lake SE of Berlin, Germany (52′27 N, 13′39 E). It has a maximum depth of 8.9 m and covers an area of 7.6 km^2. Full mixing of the lake body often takes place because of its shallowness and relatively large surface area (Driescher et al. 1993).

Lake Stechlin (Fig. 1), situated in the Baltic Lake District in NE Germany (53′09 N, 13′02 E), about 100 km N of Berlin, has a surface area of 4.1 km^2. The maximum depth is 69.5 m (Koschel and Adams 2003). Relatively large depths and small horizontal dimensions explain the dimictic character of this oligotrophic water body.

Lakes in the Berlin-Brandenburg area are lowland lakes ranging from deep to shallow, clear to less clear and from large to small surface areas. Thirty-eight Berlin-Brandenburg lakes were observed in the winter of 2008/09, ranging in mean lake depth from 0.6 to 24.2 m and from mostly less clear to clear (Table 1).

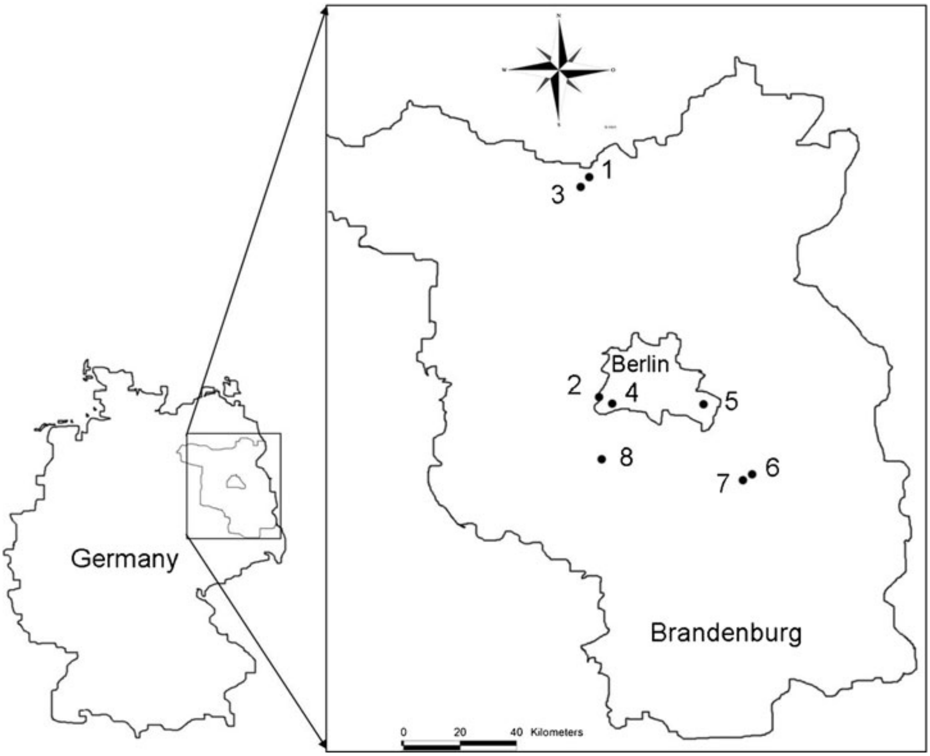

Fig. 1 Location of the lakes in Berlin and Brandenburg (Germany) for which FLake was calibrated (Müggelsee=5 and Lake Stechlin=1). Past ice coverage was modelled from 1947–2007 (eight lakes), see Table 2

Table 1 Lake specific input parameters to FLake for model calibration and validation from 1961–2007 (bold) and additional model verification for winter 2008/09

Lake number	Lake name	Mean lake depth/*maximum sampling depth* (italic) [m]	Mean Secchi-depth [m]	Mean extinction coefficient	Geographic latitude
1	**Lake Stechlin**	**24.16**	**8.5**	**0.2**	**53° 09′**
2	Großer Warthesee	13.06	2.35	0.72	53° 13′
3	Gantikower See	*12*	1.8	0.94	52° 58′
4	Trebehnsee	*11*	1.33	1.28	53° 10′
5	Oberuckersee	9.22	2.15	0.79	53° 11′
6	Schmöllner See	*9*	0.5	3.4	53° 18′
7	Gleuensee	*8*	1.1	1.55	53° 9′
8	Parsteiner See	7.05	4.6	0.37	52° 55′
9	Grünower See	*7*	1.3	1.31	53° 18′
10	Mahlgastsee	5.83	1.98	0.86	53° 6′
11	Zeesener See	5.71	1.32	1.29	52° 16′
12	Templiner See	5.47	1	1.7	53° 7′
13	Fährsee	5.13	1.13	1.5	53° 7′
14	Dunkersee	*5*	2.05	0.83	53° 15′
15	Boitzenburger Küchenteich	*5*	1.7	1	52° 54′
16	Großer Lindsee	*5*	1.4	1.21	53° 19′
17	**Müggelsee**	**4.8**	**2.13**	**0.8**	**52° 27′**
18	Klempowsee	4.47	0.76	2.24	52° 55′
19	Bruchsee	*4*	0.9	1.89	53° 8′
20	Rudower See	3.78	1.05	1.62	53° 6′
21	Zaarsee	3.69	1.57	1.08	53° 7′
22	Lychener Oberpfuhl	3.64	1.68	1.01	53° 13′
23	Mündesee	3.52	0.43	3.95	53° 1′
24	Hohennauer See	3.43	1.3	1.31	52° 40′
25	Beetzsee	3.39	0.8	2.13	52° 28′
26	Parmensee	3.31	1.08	1.57	53° 21′
27	Seddiner See	3.04	0.63	2.68	52° 16′
28	Schwielowsee	2.82	1.23	1.38	52° 20′
29	Krüpelsee	2.6	0.57	3	52° 17′
30	Germendorfer Kiessee	2.26	1.4	1.21	52° 44′
31	Petziensee	2.22	0.48	3.54	52° 21′
32	Petznicksee	2.18	0.5	3.4	53° 9′
33	Bad Branitz	*2*	0.87	1.95	51° 43′
34	Fürstenberger Bürgersee	*2*	0.6	2.83	53° 10′
35	Krebssee	*2*	0.45	3.78	52° 54′
36	Blankensee	1.18	0.33	5.23	52° 13′
37	Fienensee	*1*	0.8	2.13	53° 10′
38	Küchensee	0.58	0.53	3.21	52° 15′

Lake data from personal communication with Mr. Lehmann from IaG-GmbH (Institute for Applied Freshwater Ecology GmbH)

The sites to model lake ice since 1947 were selected to represent the diversity of the lakes in this region with respect to mean lake depth and Secchi-depth. Four lake depth classes were defined (0>d<2 m, 2≥d<5 m, 5≥d<11 m and 11≥d<25 m), with one less clear and one relatively clear lake in each lake class (Table 2). Thus, the eight selected Berlin and Brandenburg lakes (Fig. 1) were not chosen in a statistically random way.

2.2 Observed lake ice data

2.2.1 Long-term ice records

For Müggelsee, 32 years (1976–2007) of observed ice phenology data (freeze-up date, break-up date and number of ice days) are available. In addition, daily ice thickness measurements have been made for several winters. The ice phenology in Lake Stechlin, including the percentage of lake area covered with ice, has been observed from 1961 to 2001. Ice thickness observations are only available for a few days in February 1999 and January 2002.

Following Adrian et al. (1999), the freeze-up or ice start date (SD) is defined in this study as the date when more than 80% of the lake area was covered with ice, followed by a permanent ice-covered period. The break-up or ice end date (ED) is defined as the time when a lake was finally free of all ice in the spring. The sum of days with an ice cover of more than 80% is referred to as the total number of ice days per winter (ND). In contrast to the number of ice days, the ice duration (ID) is the period between freeze-up and break-up, including temporary short thawing periods in the beginning of the winter.

Observed ice phenology data showed that the shallow and less clear Müggelsee had more winters covered with ice (90.6%, $n_{obs.}$ = 32) than the deep and clear Lake Stechlin (61%, $n_{obs.}$ = 41). Furthermore, Müggelsee had more ND than Lake Stechlin (Figs. 2 and 3). Observed SD and ED of the deep Lake Stechlin were usually later than for the shallow Müggelsee. The ice cover formation was interrupted in most years by melting periods before ice cover could be established for longer periods of time. Ice formation usually started in December in Müggelsee with permanent ice cover established not before January. In Lake Stechlin, the first ice cover was usually formed in January and permanent ice cover was established in February. The differences in lake ice phenology between Müggelsee and Lake Stechlin derive from the different mixing regimes, lake depths, areas and volumes of the lakes, and may also be related to the different water quality (Table 1). Lake Stechlin has a

Table 2 Lake specific parameters of eight selected Berlin and Brandenburg lakes needed for backward modelling using FLake from 1947–2007. Lakes are sorted from deep to shallow with one relatively clear (italic) and one less clear lake (bold) in each lake depth class (according to Secchi-depth)

Lake number	Lake name	Mean lake depth [m]	Mean extinction coefficient	Geographical latitude	Mixis	Number of lake depth class	Lake depth class
1	Lake Stechlin	24.16	*0.20*	53°09′	stratified	I	11≥d<25
2	Lake Sacrow	19.30	**1.26**	52°27′	stratified		
3	Lake Nehmitz	7.14	*0.27*	53°08′	stratified	II	5≥d<11
4	Wannsee	5.50	**2.27**	52°27′	stratified		
5	Müggelsee	4.80	*0.80*	52°27′	polymictic	III	2≥d<5
6	Lake Selchow	2.82	**4.00**	52°13′	polymictic		
7	Lake Schwerin	1.68	*3.09*	52°12′	polymictic	IV	0>d<2
8	Lake Grössin	1.47	**5.31**	52°15′	polymictic		

d=class width, lake data taken from Mischke and Nixdorf (2008)

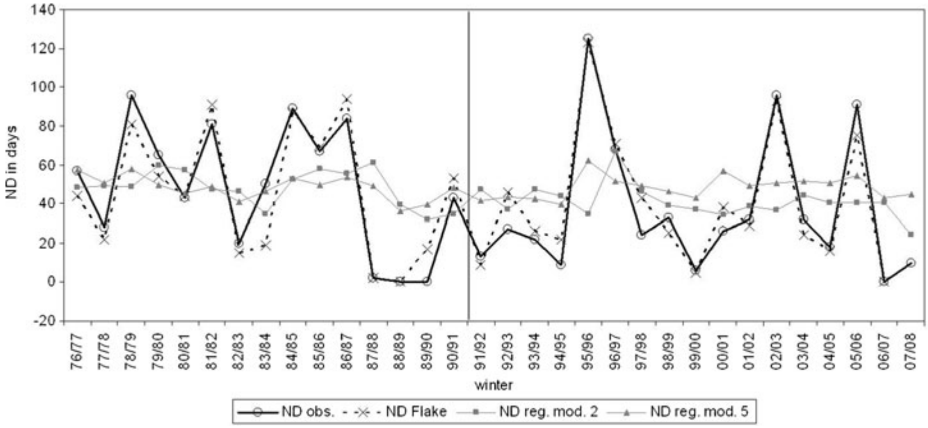

Fig. 2 Müggelsee: number of ice days (ND) for calibration (1976–1990) and validation (1991–2007) periods, modelled by FLake, two linear regression models (reg. mod.) and observed (obs.) data

volume that is three times larger than that of Müggelsee with a corresponding higher thermal inertia and later ice formation in the winter.

2.2.2 Short term ice records

A snapshot of 38 observed Berlin-Brandenburg lakes (winter 2008/09) was taken to further validate the lake model. Children from primary schools observed nearby lakes daily from mid-December to late-March throughout that winter (Fig. 4). The mean SD of these 38 Brandenburg lakes was January 1 (± 4 days) and the mean ED March 7 (± 6 days). The mean ND was 64 (± 13) days. The earliest SD was observed for the shallow (mean depth 1.2 m) and less clear (Secchi-depth 0.3 m) Blankensee on December 19 and the latest SD was observed for the deep (7.1 m) and clear (4.6 m) Parsteiner See on January 7. The moderately deep (5.7 m) and less clear (1.3 m) Zeesener See had the earliest ED, on February 23, and the latest ED was observed at the moderately deep (5.0 m) and less clear

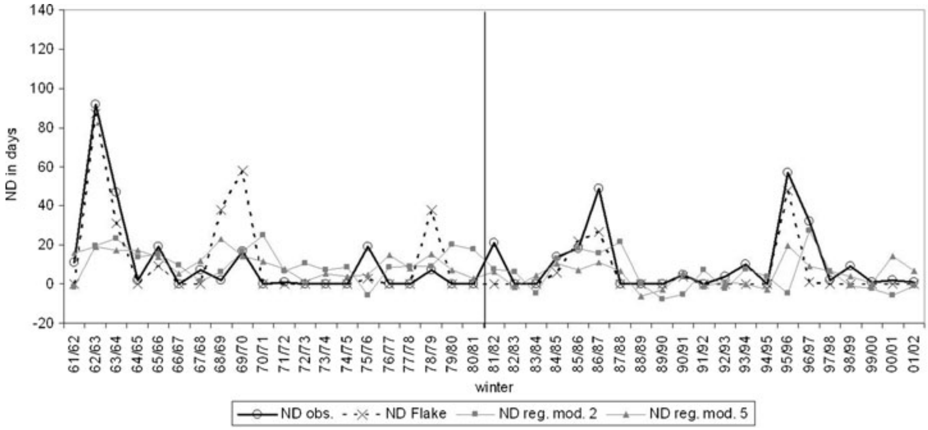

Fig. 3 Lake Stechlin: number of ice days (ND) for calibration (1961–1980) and validation (1981–2001) periods, modelled by FLake, two linear regression models (reg. mod.) and observed (obs.) data

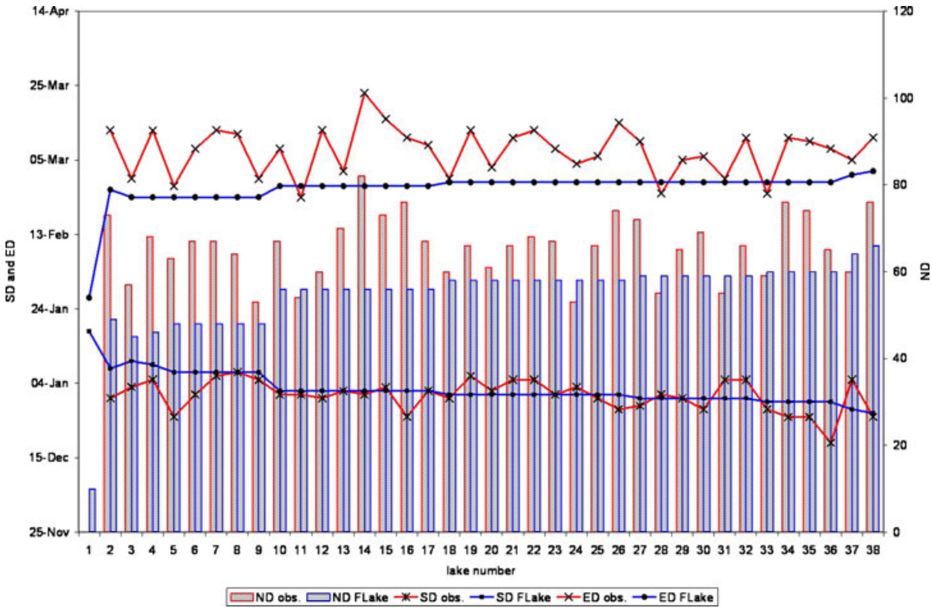

Fig. 4 Ice phenology (SD, ED and ND) for the winter 2008/2009: observed (red) and modelled by FLake (blue), showing 38 Berlin-Brandenburg lakes, sorted from deep (left) to shallow lakes (right), see Table 1

(1.4 m) Dunkersee on March 23. The lake with the most ND was Dunkersee with 82 days (Table 1).

2.3 Meteorology data

We used observed meteorological data from 1947–2007 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. DWD data included the daily sum of solar radiation (J cm^{-2}), the daily mean air temperature measured at 2 m above the ground (°C), the daily relative air humidity (%) and the daily mean wind speed (Bft). The mean daily air temperature at the Potsdam station was 9°C (± 7.8°C) from 1947 to 2007. In the past, mean annual air temperatures showed an increasing trend of 0.9 K over 60 years (or 0.015 K per year).

2.4 Models used for lake ice simulations

2.4.1 Lake model FLake

FLake is a one-dimensional model of lake temperature evolution based on a layered parametric representation of the horizontally-averaged temperature profile in a lake system including the ice cover, water column and upper lake sediments. A two-layer representation of the temperature profile is used for the lake water column. The upper layer is treated as well-mixed and vertically homogeneous. The structure of the lower stable-stratified layer is parameterised using a polynomial self-similar representation of the temperature profile. The mixed-layer depth is computed from the prognostic entrainment equation under convective conditions, and from the diagnostic equilibrium boundary-layer depth formulation under conditions of wind mixing against the stabilising surface buoyancy flux. The ice and sediment layers are treated in a similar manner, where the temperature within the sediment is approximated by a time-dependent heat wave profile (Golosov and Kirillin 2010), and a linear temperature profile across the ice cover is assumed (Mironov and Ritter 2003) with the (integral) heat budget of the ice layer. A detailed description of the model algorithm can be found in Mironov (2008).

The integral, or bulk, approach to treat the heat transfer through the ice cover is the distinguishing feature of the FLake ice sub-model. Most recently used ice models carry the heat transfer equation solved on a finite difference grid, where the number of grid points and the grid spacing differ depending on the application. With regard to ice thermodynamics, the model is broadly similar to most other models developed to date (Launiainen and Cheng 1998; Patterson and Hamblin 1988; Leppäranta 1993; Duguay et al. 2003; Leppäranta and Wang 2008). The unified bulk treatment of the ice – water column – sediment system makes FLake an attractive tool in climate research applications, where numerical efficiency and a minimum number of tunable parameters are desirable (Table 3). One of the aims of the present study was to test the model ability to reproduce the ice phenology in small temperate lakes with irregular ice cover.

Lake-specific external parameters that are not part of the model physics are needed to drive FLake. These comprise the mean lake depth, typical fetch, geographic latitude, optical characteristics of the lake water (mean extinction coefficient, ice albedo), temperature at the bottom of the thermally active layer of bottom sediments, and the depth of this layer. The five required meteorological input parameters for FLake were solar radiation (W m^{-2}), air temperature (°C), air humidity (mb), wind speed (m s^{-1}) and cloudiness (0–1). The lake model FLake was driven by measured daily average meteorological data from November 1, 1947 to October 31, 2007 (60 hydrological years) to model the ice phenology for the Berlin-Brandenburg lakes.

The model output is the daily thickness of lake ice cover, which is used to derive annual ice phenology parameters such as ice start date (SD), ice end date (ED) and number of ice days per winter (ND). Simulated SD and ED are defined as the first day of ice cover formation in the winter, when the ice thickness is non-zero, and the first day in winter without ice, when the ice thickness equals zero, respectively.

When studying lake ice and temperature evolution, the heat release from lake sediments plays an important role for shallow lakes (Duguay et al. 2003; Stefan and Fang 1997). The vertical heat transport across the lake water column from the sediment and from the deeper and warmer water layers to the ice cover takes place typically at the background of stable temperature stratification, yet exceeds significantly the conductive heat transport rates and reveals considerable lateral heterogeneity driven by temperature differences between shallow and deep parts of the lake (Terzhevik et al. 2009, Kirillin et

Table 3 Lake specific input parameters to FLake set during model calibration for Müggelsee from 1976–1990 and for Lake Stechlin from 1961–1980

Lake name	**Heat flux** between ice and water **[W m^{-2}]**	**Depth** of the thermal active layer of the bottom sediment **[m]**	**Temperature** at the outer edge of the bottom sediment **[°C]**	**Albedo** of the lake ice cover
Müggelsee	5	3	7	0.1
Lake Stechlin	3	3	7	0.1

al. 2009). These effects can only be roughly reproduced in frames of a single-column one-dimensional model, such as FLake. Therefore, we introduced an adjustable addendum to the heat flux at the lower ice boundary calculated by the original FLake algorithm. Generally, its value depends on the mean depth of the lake, complexity of the bottom topography and sediment properties. In our case, the value of the additional water-ice heat flux was the subject of the model calibration based on the time series of ice thickness. The calibration provided the values 5 Wm^{-2} for the shallow Müggelsee and 3 Wm^{-2} for the deep Lake Stechlin (Table 3). Assuming the mean depth as a major parameter affecting the vertical heat transport, we tentatively assumed the former value of 5 Wm^{-2} for the six shallow lakes (≤ 8 m mean depth, Table 1, number 7–38; Table 2, lake number 3–8) and the latter one of 3 Wm^{-2} for the deeper lakes (Table 1, number 1–6; Table 2, lake number 1–2).

2.4.2 Linear regression models

Various linear and multiple regression models to predict lake ice have been created for North American lakes (Gao and Stefan 1999; Shuter et al. 1983; Williams et al. 2004), as well as for European lakes (e.g., George 2007, Livingstone 1997, Livingstone and Dokulil 2001; Livingstone and Adrian 2009). To predict ice phenology, these models use different averages of air temperature (annual, winter, monthly), North Atlantic Oscillation-Index (annual, winter), mean lake depth and mean lake area as significant input parameters (Gao and Stefan 1999; George 2007; Livingstone 1997; Livingstone and Adrian 2009; Shuter et al. 1983; Weyhenmeyer et al. 2004; Williams and Stefan 2006). We, therefore, used these parameters as input variables for this study as well (Table 4), to predict lake ice phenology parameters of Müggelsee and Lake Stechlin, provided that the necessary ice record time series and correlated variables existed in the required resolution for both lakes.

The evolved linear regression models (Table 4) each include one lake morphological variable, mean lake depth or mean lake area, and one meteorological variable, annual mean air temperature from the Potsdam station (DWD) or winter North Atlantic Oscillation Index (mean from December–March) (Hurrell 1995). The regression models predict the ND, SD and ED for lakes representative of a distinct region.

Table 4 Linear regression models for predicting ice phenology parameters for Müggelsee and Lake Stechlin using annual air temperature (Temp N_O), winter North Atlantic Oscillation-Index (NAOI (DJFM)), mean lake depth and area. Equations labelled with *a* and *b* give identical results and those marked with+are significant ($p<0.05$) and with - are insignificant

Linear regression model	Equation number	Calibration period	Validation period
ND=89.952 - 7.201* Temp N_O	1	+	-
ND=153.944 -10.817 * Temp N_O -2.045 * mean depth	2a	+	-
ND=58.309 -10.817 * Temp N_O+11.218 * mean area	2b	+	-
SD=256.569+14.728 * Temp N_O	3	+	-
SD=210.291+17.343 * Temp N_O+1.479 * mean depth	4a	+	-
SD=279.453+17.343 * Temp N_O -8.113 * mean area	4b	+	-
ND=61.644 -2.910 * NAOI (DJFM) -2.183 * mean depth	5a	+	+
ND=-40.426 -2.910 * NAOI (DJFM)+11.973 * mean area	5b	+	+

2.5 Model calibration and validation

The calibration period was chosen as 1976–1990 for Müggelsee and 1961–1980 for Lake Stechlin, while the validation period for Müggelsee was 1991–2007 and for Lake Stechlin 1981–2001. Calibration of the lake model was done by adjusting lake-specific input parameters to FLake for each lake (Table 3) to obtain the best fit of model results with the observed ice data. For single years of the calibration period (years with ice thickness data available), the modelled and observed ice thickness evolutions were compared. For further simulations lake parameters that best fit Müggelsee and Lake Stechlin during the calibration periods (Table 3) were adapted to Berlin-Brandenburg lakes (Table 2). The thicknesses of ice covers were simulated by FLake on a daily basis for both lakes for the calibration periods and afterwards the model was validated by running scenarios for the validation periods. From these simulation results, we calculated ND, SD, ED and the duration of the ice-covered period (ID) for both from 1961–2007.

To validate the lake model for lakes with different mean lake depths and extinction coefficients, additional simulations of ice thicknesses for the winter of 2008/09 were performed for 38 Berlin-Brandenburg lakes (Table 1) and were compared with the observed ice phenology data.

Lake ice phenology observations for both lakes, Müggelsee and Lake Stechlin, were combined to construct regression models, since more than one lake is needed, when lake-specific input parameters should be included in the regression equation. The equations obtained with the data from the calibration period (Table 4) were then applied to the validation period. Significant regression models were used to calculate the ice phenology for both lakes in the time period 1961–2007.

2.6 Simulations of past lake ice phenology

The daily lake ice thicknesses of eight selected Berlin and Brandenburg lakes (Table 2) were then modelled with FLake for the past 60 years (1947–2007). Annual ice phenology data and their means for the modelled time period were analysed for the eight lakes. Trends in Potsdam air temperature and ice phenology for the eight lakes were estimated using linear trend analyses performed similar to Kirillin (2010). Trend estimates were based on annual and five-year averaged time series.

3 Results

3.1 Ice phenology modelled by FLake

3.1.1 Long term simulations

Linear correlations for observed and simulated ND for Müggelsee as well for Lake Stechlin had highly significant ($p<0.01$) Pearson's correlation coefficients squared (r^2) ranging from 0.607 to 0.927. The mean absolute error (MAE) between observed and simulated ND was between 6 and 9 days (Table 5, row 1–4). ND as modelled by FLake matched well with the observations for Müggelsee (Fig. 2, black broken line and black solid line). Model performance in simulating ND for Lake Stechlin was not as good as for Müggelsee. FLake generally slightly underestimated ND. In some cases, however, (when the winter air

Table 5 Linear correlation for observed (obs.) vs. simulated (FLake and reg. mod.) ice phenology parameters (ND, SD and ED). Pearson's correlation coefficient *r* is significant for $p<0.05$ and insignificant correlations are in italic font. The square of the correlation coefficient r^2 is shown in the table. Small mean absolute errors (MAE in days) indicate good predictions for observed data

Row number	Lake name, ice phenology parameter	Correlation	Time span	n	r^2	p	MAE
1	Müggelsee, ND	obs. vs. FLake	1976-1990	15	0.867	0.000	9.0
2	Müggelsee, ND	obs. vs. FLake	1991-2007	16	0.927	0.000	7.7
3	Lake Stechlin, ND	obs. vs. FLake	1961-1980	20	0.607	0.000	9.2
4	Lake Stechlin, ND	obs. vs. FLake	1981-2001	21	0.717	0.000	6.4
5	Müggelsee, SD	obs. vs. FLake	1976-1990	13	0.480	0.009	12.7
6	Müggelsee, SD	obs. vs. FLake	1991-2007	15	0.264	*0.050*	18.2
7	Lake Stechlin, SD	obs. vs. FLake	1961-1980	7	0.585	0.045	6.7
8	Lake Stechlin, SD	obs. vs. FLake	1981-2001	6	0.179	*0.403*	15.7
9	Müggelsee, ED	obs. vs. FLake	1976-1990	13	0.927	0.000	5.3
10	Müggelsee, ED	obs. vs. FLake	1991-2007	15	0.757	0.000	8.7
11	Lake Stechlin, ED	obs. vs. FLake	1961-1980	7	0.308	*0.196*	9.1
12	Lake Stechlin, ED	obs. vs. FLake	1981-2001	6	0.590	*0.075*	9.8
13	38 Berlin-Brandenburg lakes, ND	obs. vs. FLake	2008/09	38	0.543	0.000	6.9
14	38 Berlin-Brandenburg lakes, SD	obs. vs. FLake	2008/09	37	0.124	0.032	3.0
15	38 Berlin-Brandenburg lakes, ED	obs. vs. FLake	2008/09	37	0.001	*0.880*	5.2
16	Müggelsee, ND	obs. vs. reg. mod. 5	1976-1990	15	0.570	0.001	
17	Müggelsee, ND	obs. vs. reg. mod. 5	1991-2007	17	0.572	0.000	
18	Lake Stechlin, ND	obs. vs. reg. mod. 5	1961-1980	20	0.198	0.049	
19	Lake Stechlin, ND	obs. vs. reg. mod. 5	1981-2001	21	0.752	0.001	

temperature was low, yet no ice was observed) it strongly overestimated ND for Lake Stechlin (Fig. 3, black broken line and black solid line).

As anticipated, the fit of the observed and modelled SD was the worst of all three ice phenology parameters. The MAE was between 7 and 16 days (Table 5, row 5–8). Timing of ice-start reveals high variability between different years and is generally poorly reproducible by simplified models, both deterministic and regression. Ice formation, which takes place after surface temperatures reach the point of freezing, is governed by the processes within the air-lake boundary layer with small spatial and temporal scales and high heterogeneity. Winds may effectively prevent formation of the ice sheet from ice crystals; leading to supercooling of lake water. Relatively short calm events may result at these conditions in complete lake surface freezing within hours. In medium-size or large lakes, ice-start is a step-wise process with ice cover expanding in cold periods. The process may take a long time with gradual changes in the properties of the air-lake boundary layer. The daily resolution of the available weather data is generally too coarse to take these effects into account, producing errors in SD in the order of several weeks. Capabilities of the one-dimensional model are limited due to growth of the first ice in near-shore wind-protected areas and to variations in the heat content between shallow and deep parts of the lake which remain out of the modelling scope. The heat exchange and seasonal heat distribution processes that result in the lake's epilimnion temperature falling under 0°C, and thus determine the formation of lake ice, are described by the variables of air temperature, air humidity, wind, cloudiness, and precipitation (Livingstone and Adrian

2009). The variable precipitation, which might improve modelling results, is not included in FLake. The timing of ice cover formation is most crucial in reporting ice phenology, even though SD may be difficult to define (e.g., Futter 2003; Robertson et al. 1992). Several freeze-thaw cycles may occur early in the winter, before a lake freezes completely and for longer time spans (Adrian et al. 1999; Adrian and Hintze 2000). This uncertainty may explain the large uncertainties in predicting SD for Müggelsee and Lake Stechlin.

FLake predicted ED better than SD, but not as well as ND. The MAE for predicting ED was between 5 and 10 days (Table 5, row 9–12). This is likely due to the uncertainties in prediction of the surface albedo during the ice thaw, which usually reveals strong lateral heterogeneity and nonlinear feedbacks being in its own turn a function of incoming solar radiation. These effects are hardly reproducible within a simple one-dimensional model.

3.1.2 Short term simulations

Observed high lake-to-lake variations in ND, SD and ED were not exactly reproduced by FLake for the different 38 Berlin-Brandenburg lakes during the winter of 2008/09 (Table 5, row 13–15; Fig. 4). The MAE for predicting ND was 7 days. The correlation between observed ND and ND modelled by FLake is good and highly significant with $r^2=0.543$ ($p<0.01$), but ND was underestimated by FLake in most cases. Therefore, we looked at the model performance in reproducing SD and ED that determine ND. The fit between observed and modelled SD was very good ($r^2=0.124$, $p<0.05$, MAE=3 days), but ED was in most cases (3 exceptions) underestimated by FLake and the correlation was weak and insignificant ($r^2=0.001$, $p=0.880$, MAE=5 days). The reasons for much earlier modelled EDs than observed EDs were: the strict definition of ED (which is the time when the lake is free of all ice in spring), and the realisation of observation guidelines by pupil from primary schools. Observers may have waited until all ice floes disappeared from the entire lake surface before setting the ED. FLake as a one-dimensional model is not capable to reproduce spatially distributed thin ice floes. The thawing period was very long in that winter (ca. 15 days) and lake ice melted slowly. Therefore, differences in ice break-up observations can be big. Many observers took the ice end dates for various lakes in winter 2008/09. This may have a stronger subjective impact on the data than e.g., for Müggelsee and Lake Stechlin ice data where only one or two observers took the observation data over a much longer time span. The insufficient representation of thawing dates in the winter 2008/09 caused the poorer performance of FLake in predicting NDs of those lakes. Nevertheless, the MAE between the observed and modelled ND for the winter of 2008/09 was 6.9 days, thus in the same range as for the validation periods 1991–2007 for Müggelsee (7.7 days) and 1981–2001 for Lake Stechlin (6.4 days, Table 5, rows 2, 4 and 13).

3.2 Comparison FLake versus linear regression models

The constructed linear regression models for Müggelsee and Lake Stechlin are shown in Table 4. Three regression equations were significant for prediction of ND ($p<0.05$: eqs. 1, 2a, 2b) in the calibration period, three regression equations for SD (eqs. 3, 4a, 4b) and none of the equations for ED. The regression models 1 to 4b, which used the annual mean air temperature to predict ND and SD, were insignificant for the validation period. Regression models that predicted ND with the winter NAO-I (eqs. 5a and 5b) were significant for both the calibration and validation periods. Significant regression model results of ND for

Müggelsee and Lake Stechlin are shown in Figs. 2 and 3 (grey lines). The results of regression equations 2a and 2b as well as 5a and 5b were identical, as they use nearly the same input except for the mean lake depth and area (Table 4). Linear correlations between observed and predicted ND (for significant linear regression model 5 with $p<0.05$) for both lakes had squared Pearson's correlation coefficients (r^2) ranging from 0.198 to 0.752 (Table 5, rows 16–19).

In comparison, the deterministic lake model FLake (broken line in Figs. 2 and 3) predicted observed lake ice phenology (solid line in Figs. 2 and 3) much better than the linear regression models (grey lines in Figs. 2 and 3), also shown by greater r^2 between observed ND and predicted ND, using the FLake-simulation data instead the regression model data.

3.3 Impact of lake depth and Secchi-depth on past lake ice phenology 1947–2007

The FLake model simulated the daily ice thickness data for eight Berlin-Brandenburg lakes (Fig. 1, Table 2) and ice phenology (ND, SD and ED) was deduced from these simulations. Under the same meteorological forcing (Potsdam data), mean lake ice, as indicated by ND, SD, ED (Fig. 5) and the percentage of ice-covered winters (Fig. 6), differed for the modelled lakes, mostly due to differences in the mean lake depth (1947–2007). The more shallow a lake, the more days were ice-covered each winter, the earlier the lake started to freeze and the less winters were ice-free (Fig. 5, Table 7). Lake Secchi-depth affected the occurrence, timing, duration and thickness of lake ice as well, but less intense compared to lake mean depth (Fig. 5, Table 7). With decreasing Secchi-depth, the ND increased, the SD set in earlier and winters with ice cover increased.

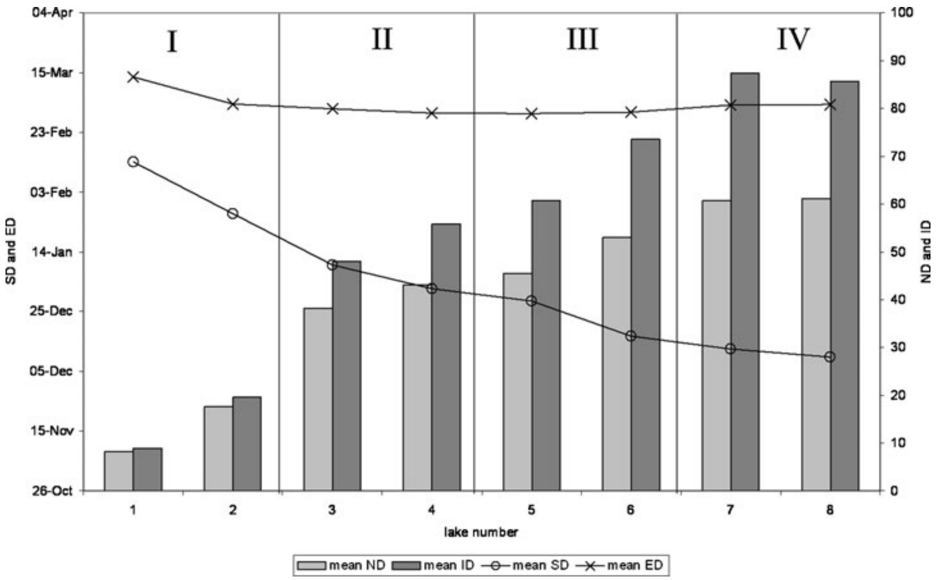

Fig. 5 Past (1947–2007) modelled mean ice phenology: ice start dates (SD) and ice end dates (ED) on the first y-axis, number of ice days (ND) and ice duration (ID) on the second y-axis. Lakes are sorted from deep (left) to shallow (right) with one relatively clear and one less clear lake in each lake depth class (I-IV). Lake numbers according to Table 2

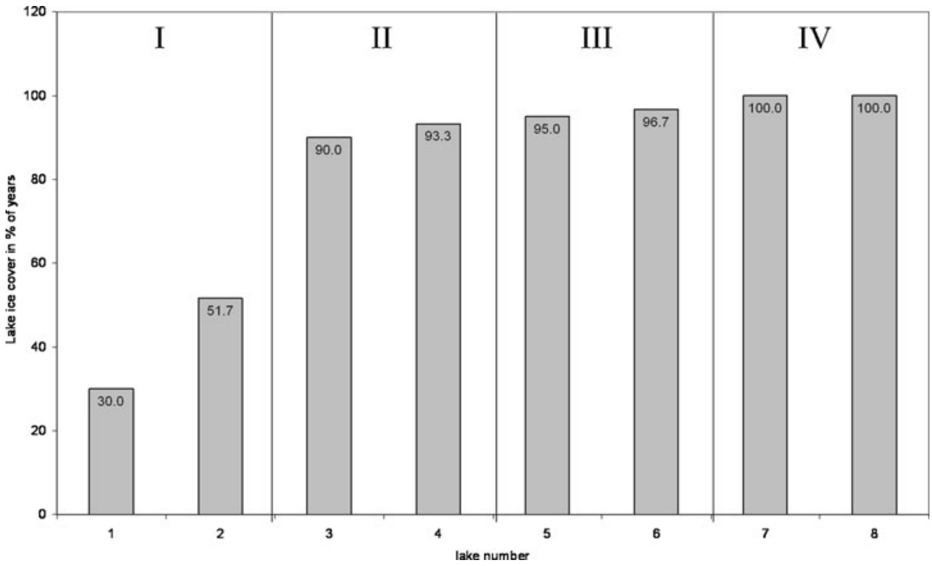

Fig. 6 Percentage of winters with lake ice cover on Berlin-Brandenburg lakes (1947–2007), sorted from deep (left) to shallow lakes (right). Each depth class (I–IV) contains two lakes with the clear water lake first and the more turbid lake second. Lake numbers according to Table 2

Impact strength and direction of lake parameters and air temperature on lake ice cover is shown in Table 7. The NDs decline with increasing mean lake depth; higher NDs were simulated for shallow lakes, e.g., Müggelsee (mean ND=46) than for deep lakes, e.g., Lake Stechlin (mean ND=8; light grey bars in Fig. 5). Clearer lakes of any lake depth class had lower mean NDs than less clear lakes. The clearer lake is the first lake in Table 2 and Fig. 5 of each lake depth class. As ND is determined by the timing of SD and ED, we scrutinized both ice phenology parameters. Lake depth, and to a smaller extent Secchi-depth, have been shown to be important parameters to determine SD. The deeper and the clearer a lake is, the longer it takes for the ice cover to form. Shallow and less clear lakes like Müggelsee freeze earlier in winter (mean SD=December 30) than deeper and more clear lakes like Lake Stechlin (mean SD=February 14; circles in Fig. 5). Furthermore, shallow lakes experienced more freezing and thawing events at the beginning of the ice period. That is indicated by the greater difference between ND and ice duration (ID) (bars in Fig. 5). For the modelled period, the mean ED of Berlin-Brandenburg lakes and its variances (not shown) were within the same narrow range (crosses in Fig. 5). In contrast to ND and SD, the end of an ice period (ED) is not affected by the mean lake depth and Secchi-depth. Still, very deep and clear lakes like Lake Stechlin had later thawing dates (mean ED=March 15) than shallower and less clear lakes like Müggelsee (mean ED=March 2). The number of ice-covered winters decreased with lake depth (Fig. 6). The shallow Müggelsee was ice-covered to 95% and deep Lake Stechlin to 30% in the winters of 1947–2007 (lakes 5 and 1 in Fig. 6, respectively). No ice-free winters were modelled for the very shallow lakes Grössinsee and Lake Schwerin (100% ice-covered winters, lakes 7 and 8) and ice covers were modelled for nearly every winter for lakes with mean depths up to 8 m (90–96.7% ice-covered winters, lakes 3–6). More winters or roughly the same amount of winters without ice cover than with ice cover were simulated (30–51.7% ice-covered winters, lakes 1 and 2 in Fig. 6) for very deep lakes like Lake Stechlin and Lake Sacrow. Lakes Secchi-depth had only a minor impact on the percentage of lake ice cover in the modelled period. Nevertheless, the more turbid a lake is, the higher the ice cover percentage (Fig. 6).

3.4 Long term trends in past lake ice phenology 1947–2007

Trends of time series of ice phenology parameters, generated from simulated lake ice thicknesses (using FLake) were analysed for the period 1947–2007. Trends in the annual mean air temperature Potsdam (Ta) and in the number of ice days (ND) of Berlin-Brandenburg lakes are shown in Figs. 7 and 8.

Linear trend analyses of air temperature revealed an increasing trend of 0.9 K (P=0.975) in Ta in 60 years, with a slope of 0.015 K each year (blue line in Fig. 7, Table 6). We calculated 5-year averages (Ta 5, red line in Fig. 7) of the air temperature time series Ta (black line in Fig. 7), because of the high year-to-year variability in annual mean air temperature. The slope of Ta 5 is 0.025 K and gives an increase in air temperature by 1.2 K (P=1.000) in 50 years (Table 6).

Declining trends of the modelled NDs emerged for all eight studied lakes with trends based on annual ND ranging from −2.6 (Lake Sacrow) to −17.3 days (Lake Nehmitz) for 60 years (Table 6 shows only trends in NDs for Müggelsee and Lake Stechlin). Due to the insignificance of these trends, we calculated linear trends of 5-year averaged ND-data (data and trends not shown). The significant (P>0.95) slopes of ND 5 range from −0.322 (Lake

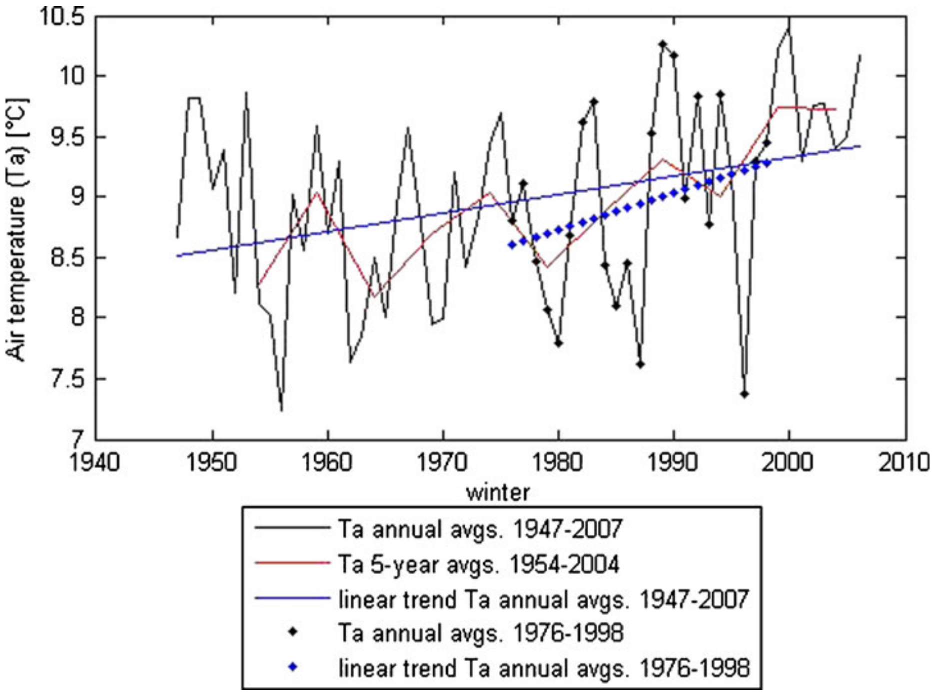

Fig. 7 Measured annual mean air temperature (black line) for Potsdam, the corresponding 5-year averages (red line) and the linear trend (blue line) 1947–2007. Additionally, the annual mean air temperature (black dots) and the corresponding linear trend (blue dots) are displayed for 1976–1998

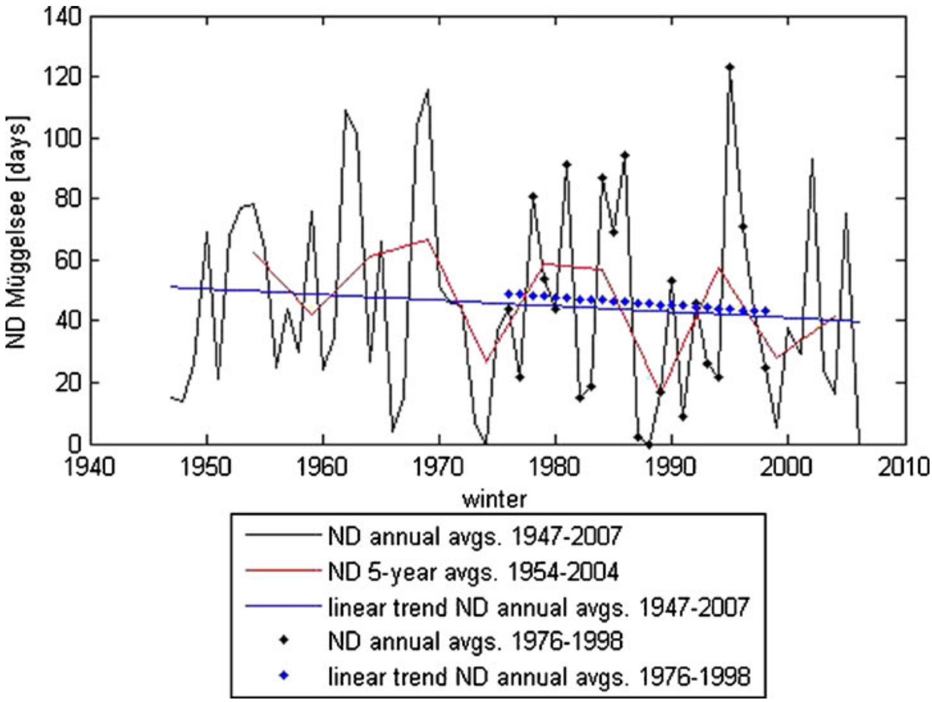

Fig. 8 Modelled number of ice days (ND) for Müggelsee (black line), the corresponding 5-year averages (red line) and the linear trend (blue line) for the period 1947–2007. Additionally, the modelled ND (black dots) and the corresponding linear trend (blue dots) are displayed for 1976–1998

Stechlin) to −0.562 days (Lake Nehmitz), similar to a decline in ND from −16.1 to −28.1 days in 50 years. Figure 8 shows Müggelsee as an example for the FLake-modelled ND-time-series of the eight lakes. The linear trend of the annual NDs (1947–2007) is −11.4 days (in 60 years) and its slope is −0.190 days. The trend of the 5-year averaged NDs is −21.8 days (in 50 years). For Lake Stechlin the decline in annual NDs is −11.3 days in 60 years, thus similar to the trend of Müggelsee (Table 6).

The linear trends of the modelled SDs for the eight lakes were mostly insignificant ($P<0.95$) and the directions of slopes were positive and negative, e.g., -7.8 days for Müggelsee and +2.6 days for Lake Stechlin in 60 years (trends not shown). The only significant trend was based on annual SD time series for Lake Sacrow with a slope of −0.179. That reveals an earlier ice start by 10.7 days in 60 years for deep Lake Sacrow. A switch from negative slopes (trends in annual averages) to positive ones (trends in 5-year averaged SDs) was observed in some linear trends of shallow lakes (Müggelsee, Lake Schwerin and Grössinsee). Thus, for these shallow lakes trends in 5-year averaged SDs showed 2.5 to 3.8 days later freezing dates in 50 years, but these trends are insignificant.

Linear trends of the modelled EDs had negative slopes for all eight studied lakes (trends not shown). Trends of annual EDs were only significant ($P>0.95$) for Lake Schwerin and Grössinsee. Trend analyses emerged for the former lake an earlier thawing by 18.9 days in 60 years and for the latter by 19.5 days. Trends of 5-year averaged EDs were all significant and the slopes ranged from −0.102 (deep Lake Sacrow) to −0.449 days (shallow Lake

Table 6 Long-term linear trends in – the measured air temperature (Ta) at Potsdam station, simulated number of ice days (ND) for Müggelsee and for Lake Stechlin – derived from annual averages and 5-year averages. To test the statistical significance of the trend estimation the test value *t** and standard error S_a were used as in Kirillin (2010). Trends are significant for P≥0.95 with $\alpha<0.05$ and insignificant trends are in italic font

Time span	1947-2007				1954-2004			
	Trend slope (a)				Trend slope (a)			
Variable	for annual avgs.	for 60-year period	$t^*=a/S_a$	P at t* for a	for 5-year avgs.	for 50-year period	$t^*=a/S_a$	P at t* for a
Ta Potsdam [K]	0.015	0.9	2.043	0.975	0.025	1.2	5.651	1.000
ND Müggelsee [days]	*−0.190*	*−11.4*	*−0.695*	*0.755*	−0.436	−21.8	−3.2	0.999
ND Lake Stechlin [days]	*−0.188*	*−11.3*	*−1.176*	*0.877*	−0.322	−16.1	−3.7	1.000

Selchow), thus trends of earlier EDs ranged for the eight studied lakes from −5.1 to −22.4 days in 50 years. The decline in EDs was for Müggelsee −16.1 days and for Lake Stechlin −4.4 days in 60 years.

In summary, trends of later SDs, earlier EDs and therefore less NDs were found in the simulated ice phenology time series from 1947–2007 for the eight lakes in north-eastern Germany.

4 Discussion

4.1 Evaluation of model performance

FLake performed well in predicting lake ice phenology for Müggelsee (Fig. 2) and Lake Stechlin (Fig. 3) during corresponding validation periods. The ND was predicted best compared to the other two ice phenology parameters SD and ED (Table 5). Nevertheless, differences between observed and modelled data occur, due to the inherent limitations of any model. These limitations are based on the physics of the problem, its simplification of reality, different definitions of modelled and observed ice phenology, measurement errors within the observed data, and meteorological conditions of the lakes that may deviate from those at the meteorological station. The errors between observed and simulated ice in the calibration and the validation periods are in the same order of magnitude for both lakes (Table 5). The mean absolute error (MAE) of ND was between 6.4 and 9.2 days and of ED between 5.3 and 9.8 days. The MAE of SD, from 6.7 to 18.2 days, was not as good as for the two other ice phenology parameters. This performance is comparable with those of published deterministic lake ice models. Root mean squared errors (RMSE) between CLIMo-simulations (Canadian Lake Ice Model) and observed data were six days for SD and four days for ED (Ménard et al. 2002).

FLake was better in reconstructing observed lake ice phenology than linear regression models (Figs. 2 and 3). Linear regression models can be adopted to gain preliminary information about the mean ice phenology of lakes in a distinct region and time window. The predicted data give an overview of ice phenology, although only a few input variables were available at a poorer time resolution. Regression models predict the long term means of lake ice phenology for the period of the ingoing variables. Results are restricted to lakes of a certain region, using the parameters of lakes taken for calibration. FLake, in turn, incorporates essentially more input information than the regression models, in particular, daily meteorology and lake-specific parameters.

We show that the lake model FLake is capable of reconstructing lake ice phenology for more turbid and shallow to clear and deep lakes with errors of only a few days (Figs. 2, 3 and 4). Even large year-to-year variability typical for observed lake ice phenology (Benson et al. 2000; Duguay et al. 2003, 2006) and intermittent ice coverage were predicted well (Figs. 2 and 3). FLake can be applied to model the (intermittent) ice covers of lakes all across the world, given knowledge about mean lake depth, Secchi-depth and meteorological parameters from a nearby weather station.

4.2 Impacts on lake ice phenology

FLake modelling results (1947–2007 and winter 2008/09) showed that lake ice phenology changes with mean lake depth, Secchi-depth and air temperature. Temperature changes have stronger effects on ice covers than lake characteristics alone can trigger.

4.2.1 Lake depth

With decreasing mean lake depth, higher NDs and a decline in ice-free winters (ND=0) and earlier SDs were modelled. With lake deepening, SD comes later, ND is lower and ice-free winters are more frequent. ED timing is not affected by lake depth (Figs. 5 and 6, Tables 2 and 7).

Lower NDs and later SDs with increasing mean lake depth have been simulated for the 38 Berlin-Brandenburg lakes in winter of 2008/09 (Fig. 4, Table 1). Correlations between mean lake depths and NDs confirm the relation of deeper mean lake depth and lower ND ($n=38$, $r=-0.959$, $p=0.000$). A reduction in ND of approximately two days (slope=−1.979) comes with every additional meter of mean lake depth. Correlations between mean lake depth and SD ($n=38$, $r=0.966$, $p=0.000$) show a 1-day delay of SDs with one meter additional lake depth (slope=0.933). Later ice start dates for deeper lakes fit our expectations, since the amount of heat stored in the lake body that determines the timing of SD increases with increasing lake depth. The higher the heat budged in the lake, the longer the cooling and the later the ice formation. Correlations between lake depth and ED were insignificant ($p>0.05$). This is mainly due to the fact that absorption of solar radiation, which governs melting of the ice cover in spring, is not directly affected by lake depth. Water temperatures under ice could potentially increase faster in more shallow lakes due to radiation heating, and would accelerate melting at the underside of the ice cover. On the other hand, mean water temperatures in winter are normally lower in shallower lakes compensating this effect. Among the lakes of the region the variations in depth are rather modest and no really deep lakes exist there.

4.2.2 Secchi-depth

With increasing mean Secchi-depth the modelled lakes (1947–2007) showed a decrease in NDs, more ice-free winters and later SDs. Hence, a reduction in Secchi-depth caused evidence of more ice days per winter, less ice-free winters and earlier SDs. There was no correlation between Secchi-depth and ND (Figs. 5 and 6, Table 7).

For the 38 Berlin-Brandenburg lakes (winter of 2008/09) correlations between mean Secchi-depth and NDs of shallow lakes (mean lake depth≤8 m, lakes 7 to 38, Table 1) revealed lower NDs for clearer lakes ($n=32$, $r=-0.597$, $p=0.000$). The correlations were conducted for the 32 shallow lakes only to ensure that the lake depth effect is not overlying effects of Secchi-depth on ice. A decline in ND of approximately 3 days (slope=−2.831)

Table 7 Influences (strength and direction) of lake and weather parameters on lake ice coverage. The impact strength is shown by the number of symbols from weak (indicated by one symbol) to strong (indicated by two symbols). If parameters do not have an impact on ice phenology, this is indicated by "no". The direction of change caused by the forcing parameters is shown by plus symbols for increase or later and minus symbols for decrease or earlier

Forcing parameter	Ice-free winters	Number of ice days per winter	Ice start date	Ice end date
lake depth +	IFW +	ND - -	SD + +	no
Secchi-depth +	IFW +	ND -	SD+	no
local winds +	IFW +	ND - -	SD +	ED - -
air temperature +	IFW + +	ND - -	SD + +	no*

* air temperature is highly correlated with solar radiation: solar radiation +, then ED - -

was detected with every increasing meter in Secchi-depth. A highly significant positive correlation was found between Secchi-depth and SD ($n=32$, $r=0.607$, $p=0.000$), thus approximately 2 days later SD (slope=1.825) with one meter improvement in visibility. The clearer a lake water during the ice-free seasons, the more heat can enter the lake body and the higher is the resulting mean temperature of the lake until the moment of freezing. Consequently, more heat has to be transported away in clear water lakes to reach the freezing temperature. Similar to the dependence of ED on lake depth, there was no significant correlation for ED with Secchi-depth. Generally, water transparency affects the vertical heat distribution within the water column under ice, and, consequently, the temperature gradient at the ice-water interface. This effect is weak in our lakes, because the upper water column is effectively mixed by the radiation-driven convection, except for the very early stage of heating, right after snow melt (Kirillin 2010). The effect of water turbidity on the ice melting rate may potentially become crucial, if the temperature of the convectively-mixed layer under the ice rises above the maximum density point (approximately 3.98°C). Then, the water column becomes gravitationally stable, and the vertical temperature gradient at the ice-water interface is fully determined by the rate of the light absorption in water. Such conditions are typical rather for polar lakes with thick ice cover, low snow amount and high solar radiation in summer (Kirillin and Terzhevik 2011).

4.2.3 Air temperature

For the period 1947–2007, bivariate Pearson's correlations between measured annual mean Potsdam air temperature (Ta) and ND were performed for the eight modelled Berlin-Brandenburg lakes. For these lakes Ta explained 32 to 40% of the variability of its modelled NDs. The correlations are significant for $p<0.05$. The reduction in ND with increasing air temperature is due to later SDs, because of high air temperatures in early winter, and earlier EDs, because of higher solar radiation which in turn is positively correlated with air temperature (Table 7).

Correlations between ice phenology and annual mean air temperature were generally stronger for shallow Müggelsee than for deep Lake Stechlin, e.g., the correlation between Ta and ND is stronger ($r^2=0.144$) for Müggelsee than for Lake Stechlin ($r^2=0.113$). Both correlation coefficients are highly significant for $p<0.001$.

We correlated Müggelsee ice phenology parameters (ND, SD and ED) each with Potsdam air temperature Ta (1947–2007 and 1976–1998) and compared the slopes of the linear regression lines to other studies. Figures 7 and 8 (blue dots) show an increasing trend in Ta and a declining trend in ND for both periods. We note that the definitions of ice phenology parameters are slightly different in the cited studies. Therefore, direct comparisons can only be made with the results of Adrian and Hintze (2000), who worked with the same definitions as we did. According to FLake simulations, a 1 K warmer annual air temperature for the period 1947–2007 revealed a 15.6 days lower ND ($n=60$, $r^2=0.144$, $p=0.003$, Fig. 9 top), 5.7 days later SD and 6.8 days earlier ED for the shallow Müggelsee. To compare these results from simulated ice phenology data by FLake with observed results from Adrian and Hintze (2000), we used the same period. A 1 K annual air temperature increase revealed 13.3 days lower ND for 1976–1998 (Fig. 9 bottom), 3.3 days later SD and 6.1 days earlier ED for Müggelsee. Similar magnitudes of changes in ice phenology with rising air temperatures (December-February and January means instead of annual mean) were presented by Adrian and Hintze (2000): A 1 K increase in mean winter air temperature (December-February) in Berlin (1976–1998) resulted in a 16.7 day shorter ice-covered

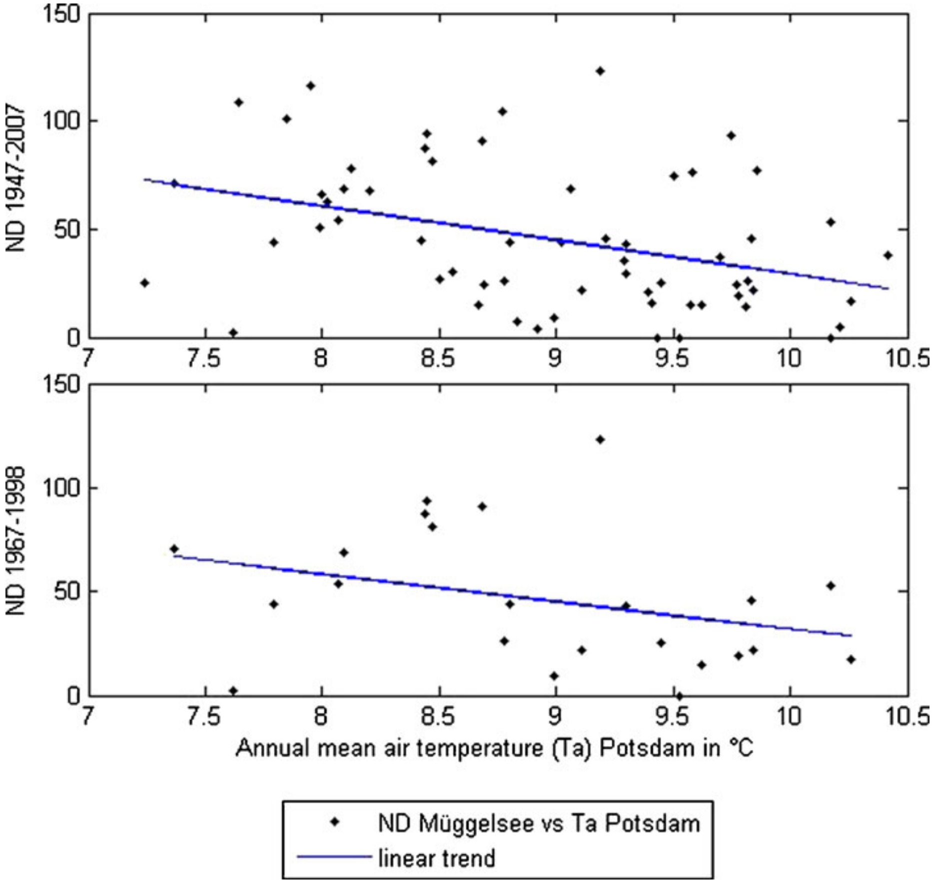

Fig. 9 Müggelsee: number of ice days (ND) versus annual mean air temperature (Ta) Potsdam (black dots) and the corresponding linear trends (blue lines), displayed for 1947–2007 (top) and 1967–1998 (bottom)

period (ND) and a 9 day earlier ED at Müggelsee, while a 1 K increase in the mean January air temperatures was best correlated with SD, leading to a 3.8 day later SD at the lake. Studies of Canadian lakes found that the SD of lake ice occurred approximately 5 days later, ED approximately 6 days earlier and ND was approximately 11 days lower for every Kelvin increase in annual mean air temperature (Duguay et al. 2003; Morris et al. 2005; Williams et al. 2004).

The ice phenology parameters ND and SD change, but ED is nearly the same with changing mean lake depth and Secchi-depth (Fig. 5). SD is the ice phenology parameter that is affected by lake depth and Secchi-depth, because both determine lakes heat capacity and heat loss rate, which control the timing of ice formation. NDs only change with lake depth and Secchi-depth because of changes in SD. A significant correlation was determined between EDs and the local air temperature. However, the timing of ED is affected by geographical location (solar radiation) and ice and/or snow characteristics and only indirectly affected by air temperature (Table 7). While the effect of air temperature on the melting rate is minor compared to the solar heating, the former appears to represent a good indicator of the processes governing ice melting. At the latitudes of northern Germany, the radiation amount in winter remains relatively high as compared to higher latitudes. In turn, the snow thickness, determining the surface albedo and, consequently, penetration of the solar radiation, is typically low here and may be quickly destroyed, e.g., by rain. As a result, both air temperature and radiation absorption at the ice surface are affected by short-term changes in local weather. This makes the instant air temperature an appropriate predictor of the ice melting date, at least in temperate lowland areas.

4.3 Trends in ice phenology

Linear trends in Potsdam air temperature and FLake modelled lake ice data for the eight Berlin-Brandenburg lakes (annual averages and 5-year averages) are presented for the periods 1947–2007 and 1954–2004, respectively.

Trends of decreasing NDs (−9.5 to −28.1 days in 50 years), of earlier EDs (−5.1 to −22.4 days in 50 years), and of increasing ice-free winters (thus a more frequent occurrence of winters with ND=0 with time) emerged in simulated ice data (Table 7). The increasing number of ice-free winters agrees with results of Adrian and Hintze (2000) about increased amount of winters with no ice cover in lakes of western and central Europe. Most linear trends of SD were insignificant, but showed earlier ice start dates in most cases for deep lakes (up to −6.4 days), and later ice start dates for shallow lakes (2.5 to 3.8 days in 50 years; data not shown). Trends in air temperature (Ta) showed rising Ta by 1.2 K in 50 years (Fig. 7, Table 6).

Since a larger lake body can store more heat and releases it more slowly (Livingstone 2008), deep lakes of higher volume provide a kind of “low-pass” filter for the atmospheric forcing: the sensitivity of their ice regime to year-to-year variations in the local weather is lower than that of shallow lakes (cf. the ratio of the linear trend to the variance *a/Sa* for air temperature, ND in deep Lake Stechlin and ND in shallow lake Müggelsee in Table 6). Hence, the long-term trend is more significant in the ice phenology records from deep lakes.

The order of magnitude of emerged trends in lake ice phenology (1947–2007) is similar to that of trends in lake and river ice in the northern hemisphere (1846–1995) detected by Magnuson et al. (2000a): The trends in this study revealed a 5.8 day later SD and 6.5 day earlier ED per 100 years with an increase in air temperature of 1.2 K per 100 years. Our period of trend estimation is shorter than that used by Magnuson et al. (2000a). This complicates direct comparison of the trend values from the two studies, since the trends do not necessarily remain linear during the periods of estimation. Our estimation period coincides roughly with the second half of that used by Magnuson et al. (2000a); the trend slopes in the earlier ED’s are, in turn, at least twice as steep. This suggests a growing rate of change of the ice phenology characteristics in the most recent time, which qualitatively agrees with recent estimates of the mean trends in northern hemisphere lakes over the past 30 years (Magnuson, pers. comm.).

5 Conclusions

This study modelled past ice phenology for a variety of freshwater lakes in the Berlin-Brandenburg area, Germany, to reconstruct trends in past ice regimes for lakes without ice observations.

We show that the deterministic lake model FLake performs better at reconstructing past lake ice cover than linear regression models. FLake computes reasonable ice results (daily resolution) for shallow, relatively turbid and polymictic lakes, as well as for deep, clear and stratified small lakes. The model reproduces lake ice dynamics well, including the high annual variability of ice phenology and the intermittent ice cover per winter. Therefore, FLake is a reliable tool to study lake ice phenology. FLake can be applied to model ice covers on lakes around the world, provided that lake characteristics such as mean lake depth, Secchi-depth, and representative meteorological parameters near the lakes are known. Additional advantages of FLake are its free availability on the internet, its easy application, the limited input parameters needed and its related computational efficiency.

Simulated ice phenology for eight contrasting Berlin-Brandenburg lakes indicated depth-dependent lake ice cover. Deeper lakes have shorter ice-covered periods (ND −2 days with every meter increase in lake depth), later freezing dates (SD +1 day with every meter increase in lake depth) and more ice-free winters than more shallow lakes. We found lake ice cover to be dependent on the trophic state, but this effect was weaker than that of lake depth. Clearwater lakes had shorter ice-covered periods (ND −3 days with every meter increase in Secchi-depth), later ice cover freezing dates (SD +2 days with every meter improvement in visibility) and more ice-free winters than less clear lakes. Simulations show that freezing dates vary much more strongly with changing lake depth than thawing dates; thus, ice cover formation determines the duration of the ice period. The number of ice days per winter, the ice start date and the number of ice-covered winters are affected by parameters that determine heat storage and heat release of a water body. In contrast, the ice end date depends on solar radiation as well as on ice and snow characteristics.

Absolute trend values in ice phenology were found to be higher for more shallow lakes. Thus, trends in ND ranged from −10 to −28 days and trends in ED from −5 to −22 days from the deepest to the shallowest lake in the 5-year averaged time series, including a cumulative trend of +1.2 K in the 5-year averaged air temperature time series over 50 years (1954–2004).

We showed a decline in lake ice cover associated with global climate warming and local air temperature increase for Berlin and Brandenburg lakes. Trends of later freezing, e.g., for Müggelsee (+5.7 days) and earlier thawing (−6.8 days), shortening in ice duration (−15.6 days), thinning of the ice cover and an increasing number of ice-free winters were modelled for the period 1947–2007, including a cumulative trend of a 1 K annual mean air temperature increase over 60 years. Past trends of ice reduction are of the same order of magnitude as those reported elsewhere (e.g., Magnuson et al. 2000a).

Changes in lake ice may lead to changing water temperatures, mixing regimes, and oxygen, nutrient and light levels. These changes will affect species composition and abundance. Thus, lake food webs are likely to be altered, eventually causing mismatches (Fritsen and Priscu 1999; Winder and Schindler 2004). Modelling of lake ice is important for climate impact studies in order to predict the effects on ecosystems under different climate scenarios, e.g., for lake management. For many different lakes and regions, projections of climate warming effects on lake ecosystems can be assessed with the help of: (i) regional climate models, (ii) physical lake models capable of predicting ice cover (like FLake) and (iii) lake ecosystem models.

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