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An automated method to monitor lake ice phenology

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Abstract

A simple method to automatically measure the date of ice-on, the date of ice-off, and the duration of lake ice cover is described. The presence of ice cover is detected by recording water temperature just below the ice/water interface and just above the lake bottom using moored temperature sensors. The occurrence of ice-on rapidly leads to detectable levels of inverse stratification, defined as existing when the upper sensor records a temperature at least 0.1°C below that of the bottom sensor, whereas the occurrence of ice-off leads to the return of isothermal mixing. Based on data from 10 lakes over a total of 43 winter seasons, we found that the timing and duration of inverse stratification monitored by recording temperature sensors compares well with ice cover statistics based on human observation. The root mean square difference between the observer-based and temperature-based estimates was 7.1 d for ice-on, 6.4 d for ice-off, and 10.0 d for the duration of ice cover. The coefficient of determination between the two types of estimates was 0.93, 0.86, and 0.91, respectively. The availability of inexpensive self-contained temperature loggers should allow expanded monitoring of ice cover in a large and diverse array of lakes. Such monitoring is needed to improve our ability to monitor the progression of global climate change, and to improve our understanding of the relationship between climate and ice cover over a wide range of temporal and spatial scales.

For lakes, changes in the timing of ice-on and ice-off, along with changes in the duration of ice cover, have been clearly

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†This paper was originally conceived by Pierson and Weyhenmeyer using data from Lake Erken. Later the paper was expanded to include additional sites, and the remaining co-authors contributed data and assisted in preparing the manuscript. Because of equal contributions the remaining authors are listed alphabetically.

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established as sensitive indicators of climate change (e.g., Magnuson et al. 2000). Long-term trends toward later ice-on and earlier ice-off, presumably associated with global warming, have been detected in Canada (Skinner 1993; Duguay et al. 2006), Finland (Palecki and Barry 1986; Korhonen 2006), Switzerland (Livingstone 1997), and in the New England (Hodgkins et al. 2002) and North Central regions of the United States (Robertson et al. 1992; Johnson and Stefan 2006; Jensen et al. 2007). Simulations of future ice cover dynamics based on Global Climate Model (GCM) output also suggest that the duration of lake ice cover will decrease as result of global warming (Fang and Stefan 1998, 1999; Stefan et al. 1998).

Because changes in the timing and duration of ice cover influence lake biology and biogeochemistry, they can be expected to be an important mechanism through which the effects of global warming are transferred to lake ecosystems (Blenckner 2005). The timing of ice-off has been shown to influence the timing, magnitude, and composition of the phytoplankton spring bloom (Pettersson 1990; Adrian et al. 1999; Weyhenmeyer et al. 1999), and winter oxygen concentrations

(Fang and Stefan 1997; Wiedner and Nixdorf 1998; Phillips and Fawley 2002). The timing of ice-out may also influence spring and summer lake water temperatures (Austin and Colman 2007, 2008), with longer-term effects on hypolimnetic temperatures following thermal stratification (Livingstone 1993; Gerten and Adrian 2001; Straile et al. 2003).

Ice phenology data are still most commonly recorded by visual observation. The use of satellite remote sensing for this purpose is becoming more and more common (Wynne et al. 1996; Wynne et al. 1998; Latifovic and Pouliot 2007), and it has been shown that satellite-derived estimates of ice cover phenology, particularly ice loss, are close to observer-based estimates (Wynne et al. 1996). The utility of satellite remote sensing, however, is limited by the occurrence of cloud cover and by the fact that it is generally only suitable for large lakes (e.g., >10 km²). While ice phenology is strongly related to global and regional climatic forcing, local conditions such as topography, lake basin morphometry, and snow accumulation patterns also play a role (Williams et al. 2004). Monitoring the ice cover of a large number of lakes over a large spatial extent would therefore, allow the mechanisms responsible for local variations in ice cover to be better understood, and would also allow estimates of regional variations in ice cover to be made that more adequately account for local variability. When surveying regional variations in ice cover, it can be especially important to include lakes of all size and remote lakes in sparsely populated areas where dedicated human observers are not available and where frequent sampling is not possible.

To increase the consistency of ice cover measurements, and to make it possible to record routinely the timing and duration of ice cover on large numbers of lakes, a simple automated method to detect ice cover is needed. We demonstrate the utility of a method based on automatic water temperature measurements that uses the timing of the beginning and end of inverse thermal stratification as an indicator of the timing of ice-on and ice-off. This simple method for estimating the timing and duration of ice cover is tested on a number of lakes and reservoirs, most of which are part of the Global Lakes Ecological Observatory Network (GLEON; www.gleon.org). Given the simplicity of the method, the availability of inexpensive autonomous temperature loggers, and the clear need for expanded lake ice monitoring, we suggest that such temperature-based ice-phenology measurements can supplement present efforts to monitor lake ice. The purpose of this article is to systematically compare estimates of the onset, loss, and duration of ice cover based on the proposed temperature-based estimation method and estimates based on visual observation. We also examine the effects of using two different temperature sensor deployments with the proposed temperature-based method; a surface temperature sensor moored at a shallow depth that freezes into the ice cover, or a surface sensor moored just below the maximum depth of the ice.

Materials and procedures

The lakes and reservoirs included in this study are listed in Table 1. All have systems for recording lake water temperatures automatically that are deployed during the winter ice season, and all have independent, observer-based estimates of the timing and duration of lake ice cover. For all lakes, relevant meteorological data, such as wind speed, solar radiation, and air temperature, are available that are measured either on the same monitoring buoy that carries the water temperature measuring system or at a nearby meteorological station. At Lake Erken, Sweden, from which much of our data were obtained, the water temperature is measured at 3 depths (1.0, 3.0, and 15 m) using thermocouple sensors that are moored year-round in the lake (Table 2); in addition, there is a permanent lake monitoring station located on a small island approximately 500 m from shore and 100 m from the deepest part of the lake at which a number of routine meteorological measurements are made.

A number of relatively inexpensive (approximately \$150–\$200) autonomous temperature logging systems are commercially available that would be suitable for detecting ice cover as we describe here. Two such systems (manufactured by Vemco and Onset) are used at sites included in this study (Table 2). These systems are hermetically sealed, contain a long-life battery, and are capable of logging water temperature data over at least a six-month period. Once retrieved, data can be downloaded as an optical signal transmitted through the temperature logger housing. The great advantage of these systems is that they can be rapidly deployed and do not require underwater cabling and an onshore data logger installation, as used at Lake Erken. These systems could, therefore, be deployed in large numbers of lakes to provide a better understanding of local and regional variability in lake ice phenology.

Two different mooring configurations were used at the different lake sites listed in Table 1. At some sites, the uppermost sensor was deployed at a depth just below the expected maximum depth of ice cover. In Lake Erken, for example, the uppermost sensor was permanently moored at a depth of 1 m (Fig. 1), so ice movements had no effect on the installation. Sensors at Lake Erken have performed reliably without maintenance for periods of up to 10 y. An alternative is to place one sensor at a shallow depth (e.g., 0.1 m) and for the mooring buoy to be deployed at, rather than below, the surface. This mooring configuration is more precise in detecting the timing of ice-on and ice-off, but requires greater maintenance, and also requires sensors that can withstand being frozen into the ice. It is well suited for autonomous temperature loggers, as the recorded data must be retrieved from these regularly, allowing the mooring to be checked and redeployed immediately after data retrieval.

From the water temperature time series, the period of ice cover can be discerned as the period during which inverse thermal stratification is continually recorded. The boundary between isothermal and inversely stratified conditions is quite

Table 1. Details of ice phenology estimates. Mean values are calculated for both estimates of onset, loss, and duration of ice cover and the difference between methods. Means also show 95% confidence interval. The root mean square of the differences is calculated.

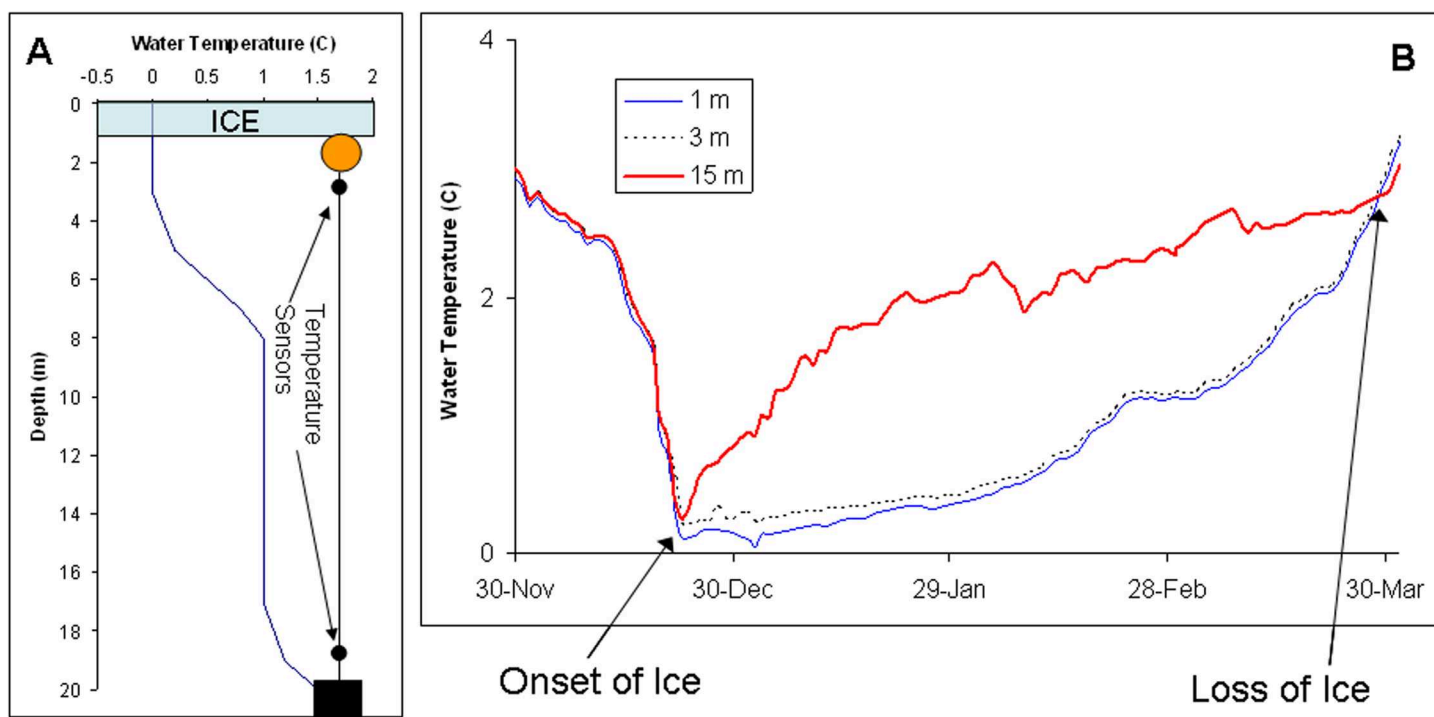
Lake	Location	Winter	Data from temperature sensors			Visual observations			Observed determined minus temperature determined estimates		
			Onset	Loss	Duration	Onset	Loss	Duration	Onset	Loss	Duration
Erken	Sweden	1988-1989	2-Dec-88	5-Feb-89	65	1-Dec-88	3-Feb-89	64	-1	-2	-1
Erken	Sweden	1989-1990	6-Dec-89	7-Dec-89	6-Feb-90	61	1				
Erken	Sweden	1990-1991	14-Jan-91	27-Mar-91	72	11-Jan-91	21-Mar-91	69	-3	-6	-3
Erken	Sweden	1991-1992	23-Jan-92	22-Mar-92	59	25-Jan-92	12-Mar-92	47	2	-10	-12
Erken	Sweden	1992-1993	18-Mar-93	21-Feb-93	18-Mar-93	25		0			
Erken	Sweden	1995-1996	29-Nov-95	16-Apr-96	139	28-Nov-95	15-Apr-96	139	-1	-1	0
Erken	Sweden	1996-1997	20-Dec-96	18-Mar-97	88	18-Dec-96	13-Mar-97	85	-2	-5	-3
Erken	Sweden	1997-1998	2-Feb-98	1-Feb-98	4-Apr-98	62	-1				
Erken	Sweden	1998-1999	20-Dec-98	4-Apr-99	105	20-Dec-98	9-Apr-99	110	0	5	5
Erken	Sweden	1999-2000	22-Dec-99	27-Mar-00	96	29-Dec-99	16-Apr-00	109	7	20	13
Erken	Sweden	2000-2001	13-Jan-01	9-Apr-01	86	19-Jan-01	9-Apr-01	80	6	0	-6
Erken	Sweden	2001-2002	23-Dec-01	29-Mar-02	96	15-Dec-01	4-Apr-02	110	-8	6	14
Erken	Sweden	2002-2003	7-Dec-02	8-Dec-02	5-Apr-03	118	1				
Erken	Sweden	2003-2004	30-Dec-03	1-Apr-04	93	30-Dec-03	14-Apr-04	106	0	13	13
Erken	Sweden	2004-2005		8-Apr-05		27-Jan-05	11-Apr-05	74		3	
Erken	Sweden	2005-2006	4-Jan-06	22-Apr-06	108	1-Jan-06	24-Apr-06	113	-3	2	5
Erken	Sweden	2006-2007	27-Jan-07	24-Mar-07	56	24-Jan-07	1-Apr-07	67	-3	8	11
Erken	Sweden	2008-2009	6-Jan-09	10-Apr-09	94	3-Jan-09	14-Apr-09	101	-3	4	7
Mälaren/Galten	Sweden	1998-1999	22-Nov-98	10-Apr-99	139	19-Nov-98	8-Apr-99	140	-3	-2	1
Mälaren/Galten	Sweden	1999-2000	15-Dec-99	26-Mar-00	102	14-Dec-99	22-Mar-00	99	-1	-4	-3
Mälaren/Galten	Sweden	2000-2001	12-Jan-01	14-Jan-01	2						
Mälaren/Ekoln	Sweden	1998-1999	11-Jan-99	1-Apr-99	80	11-Jan-99	8-Apr-99	87	0	7	7
Mälaren/Ekoln	Sweden	1999-2000	31-Dec-99	23-Apr-00	114	31-Dec-99	17-Apr-00	108	0	-6	-6
Mälaren/Ekoln	Sweden	2000-2001	10-Jan-01	14-Jan-01	4						
Pääjärvi	Finland	2000-2001	4-Jan-01	30-Apr-01	116	20-Jan-01	25-Apr-01	95	16	-5	-21
Valkea-kotinen	Finland	2002-2003		26-Apr-03		18-Oct-02	7-May-03	201		11	
Valkea-kotinen	Finland	2003-2004	10-Nov-03	21-Nov-03	28-Apr-04	159	11				
Valkea-kotinen	Finland	2004-2005	16-Nov-04	16-Nov-04	26-Apr-05	161	0				
Sparkling	Wisconsin	1999-2000	8-Dec-99	2-Apr-00	116	16-Dec-99	2-Apr-00	108	8	0	-8
Sparkling	Wisconsin	2000-2001	28-Nov-00	14-Apr-01	137	2-Dec-00	22-Apr-01	141	4	8	4
Sparkling	Wisconsin	2001-2002	13-Dec-01	24-Apr-02	132	25-Dec-01	18-Apr-02	114	12	-6	-18
Sparkling	Wisconsin	2002-2003	24-Nov-02	22-Apr-03	149	26-Nov-02	24-Apr-03	149	2	2	0
Sparkling	Wisconsin	2003-2004	21-Nov-03	20-Apr-04	151	2-Dec-03	17-Apr-04	137	11	-3	-14
Sparkling	Wisconsin	2004-2005	21-Nov-04	10-Apr-05	140	16-Dec-04	14-Apr-05	119	25	4	-21
Sparkling	Wisconsin	2005-2006	20-Nov-05	2-Dec-05	13-Apr-06	132	12				
Trout Bog	Wisconsin	2003-2004	12-Nov-03	21-Apr-04	161	8-Nov-03	20-Apr-04	164	-4	-1	3
Trout Bog	Wisconsin	2004-2005	19-Nov-04	13-Apr-05	145	23-Nov-04	14-Apr-05	142	4	1	-3
Trout Bog	Wisconsin	2005-2006	28-Nov-05	21-Nov-05	12-Apr-06	142	-7				
Ashokan Reservoir	New York	2004-2005	19-Jan-05	31-Mar-05	71	14-Jan-05	1-Apr-05	77	-5	1	6
Rondout Reservoir	New York	2004-2005	16-Jan-05	9-Apr-05	83	24-Jan-05	4-Apr-05	70	8	-5	-13
Rondout Reservoir	New York	2006-2007	14-Feb-07	27-Mar-07	41	12-Feb-07	28-Mar-07	44	-2	1	3
Rondout Reservoir	New York	2007-2008	9-Feb-08	22-Mar-08	42	2-Feb-08	31-Mar-08	58	-7	9	16
Lake Sunapee	New Hampshire	2007-2008	29-Nov-07	22-Apr-08	145		23-Apr-08	1			
Mean (all data)			20 Dec ± 8.3d	6 Apr ± 5.4d		23 Dec ± 8.3d	7 Apr ± 5.5d		2.1 ± 2.1	1.5 ± 2.1	-0.8 ± 3.6'
RMS Difference (all data)									7.1	6.4	10.0

Table 2. Temperature sensor and data logger information.

Site	Logger and sensor information	Temperature resolution	Upper and lower depths (m)
Lake Erken, Sweden	Campbell Scientific CR10 Thermocouple Temperature Sensors	0.05°C*	1.0, 15.0
Lake Sunapee, New Hampshire	Campbell CR10 and Apprise Technology Templine	0.1°C†	0.1, 13.0
Wisconsin Lakes	Apprise Technology. TempLine	0.1°C†	
Sparkling			0.01, 18.0
Trout Bog			0.01, 7.0
New York City Reservoirs	Vemco Minilog 12 bit self-contained temperature logger	0.015°C†	
Ashokan			0.5, 48.0
Rondout			3.0, 43.0
Finland Lakes	Vemco Minilog 8 bit self-contained temperature logger	0.2°C†	
Pääjärvi			0.2, 40.0
Valkea-kotinen			0.5, 4.5
Lake Mälaren Basins, Sweden	Onset Stow Away, 8 bit self-contained temperature logger	0.2°C†	
Ekoln			1.0, 28.0
Galten			1.0, 8.75

*Based on actual measurements—includes noise resulting from a long cable length to 15 m sensor

†Manufacturer specifications

**Fig. 1.**

clear, and from temperature time-series such as those illustrated in Fig. 1B, it is possible to estimate the timing and duration of ice cover by simple visual inspection. However, to maintain the greatest possible consistency when comparing different time periods and different sites, we used a simple algorithm to define the presence of ice cover. In most cases, lakes were classified as ice-covered any time the temperature

difference between the bottom and top temperature sensors was greater than 0.1°C. The top sensor used in these calculations was always the shallowest deployed and varied in depth from 0.01–3.0 m at different sites (Table 2). This method can detect ephemeral ice formation when ice forms for relatively short periods of time (i.e., days-weeks), or more permanent ice cover that forms for a large portion of the winter (i.e., weeks-

months), and which is characteristic of all of the lakes in Table 1. Inverse stratification also can occur briefly without the development of ice. This is normally a short-term phenomenon (hours-days) that could give a false indication of ephemeral ice cover. Permanent ice cover was considered to occur over the longest continuous period during any winter when the temperature difference exceeded the 0.1°C threshold. The purpose of separating permanent ice cover from ephemeral ice cover was to allow comparisons with the available observer-based estimates, which record continuous ice cover as a single set of ice-on and ice-off dates. For lakes with 8-bit loggers, which have a temperature resolution of 0.2°C (Table 2), the same methodology was used, but ice-cover was considered to be present when the temperature difference exceeded 0.4°C rather than 0.1°C . Whereas the higher resolution temperature measurements are preferable, tests using both thresholds with data from Lake Erken found that, on average, the 0.4°C threshold resulted in the onset of ice cover being estimated 4 d later and the loss of ice cover being estimated 3 d earlier, showing that the lower resolution data could produce meaningful but less precise estimates.

Independent estimates of the calendar dates of ice-on and ice-off were obtained by visual observation at all of the sites listed in Table 1. The exact protocol for making such observations varied from lake to lake, often depending on the existence of a regular lake sampling program (the New York City Reservoirs and Wisconsin lakes), on the proximity of the lake to a field station/research lab (Wisconsin Lakes, Lake Erken, and Lake Pääjärvi), or on interested local observers (Lake Sunapee, Lake Mälaren). Factors such as the frequency of observation and the perception of what constitutes ice cover (i.e., partial as opposed to complete freeze over) adds uncertainty to the data used to verify our temperature-based calculations of the timing of ice-on and ice-off. There are errors in both temperature-derived and observer-based estimates of ice cover, and there are no clear trends in Table 1 suggesting one estimate is more accurate than the other. For example, one of the largest differences in Table 1 is for Lake Pääjärvi, the site of a university field station where visual observations are frequently made, whereas relatively small differences were obtained for Lake Mälaren where the lower resolution temperature sensors were used. Consequently, when comparing these estimates, we refer to differences between them rather than an error in either of the methods.

To provide a quantitative index of the difference between observer and temperature based estimates of ice phenology, mean values of temperature based and observation based estimates of the onset loss and duration of ice cover are given in Table 1. The mean, as well as the root mean square (RMS) of the differences between yearly estimates of ice-on, ice-off and ice cover duration, are also given in the same table. In the case of Lake Erken, we also compare the trend in ice cover derived from both visual observation and temperature measurements with local variations in air temperature measured at the lake.

Assessment and discussion

The data in Fig. 1B illustrate how ice cover can be detected by placing two water temperature sensors in a lake as described above. Ice-on is characterized by a separation of the water temperatures, as the lake surface cools to approach 0°C and the bottom temperature gradually increases as a result of sediment heating. Loss of ice cover leads to a breakdown of this temperature gradient and a return to isothermal conditions. This method is hardly novel; various studies have adopted a similar approach, making the tacit or explicit assumption that the behavior of water temperatures measured using single or multiple thermistors are strongly linked to the timing of ice-on and ice-off (Schmidt et al. 2004; Thompson et al. 2005; Šporka et al. 2006). We are not, however, aware of a systematic comparison of temperature-based and observer-based ice phenology data as presented here.

The timing of ice-on, timing of ice-off, and the duration of ice cover were calculated for all 10 sites listed in Table 1, for all years for which both observer-based ice phenology estimates were available and temperature-based ice phenology estimates could be calculated. The observer-based and temperature-based ice phenology estimates correspond well (Fig. 2), although in some cases, there were relatively large positive or negative residuals between the two estimates (Table 1). These tended to cancel out so that over the 43 cases examined the average observation-based and temperature-based estimate of the onset and loss of ice cover agreed within 1–2 d. The RMS difference between the two estimates ranged from 6–10 d, and a linear regression between the two estimates yielded a gradient that was not statistically different ($P < 0.01$) from a 1:1 relationship (Fig. 2).

For lakes where the upper sensor was moored below the ice (Table 2), the relationship describing the timing of ice-off showed several cases where there were relatively large positive differences (Table 1), suggesting a bias that would lead to the temperature-based estimates indicating an earlier ice-off date than the observer-based estimates. Estimates of the duration of ice cover encompass discrepancies associated with both ice-on and ice-off, and as a result show a somewhat greater RMS difference than either of these (Table 1).

One possible explanation for the apparent bias toward early estimates of the timing of ice-off exhibited by the proposed temperature method can be offered based on the temperature time-series of three sensors in Lake Sunapee (Fig. 3), where the uppermost sensor was allowed to freeze into the ice. From these data, it is apparent that even though the lake became isothermal between 0.5 m and the lake bottom on 7 April 2008 (an indicator similar to that used at Lake Erken for the occurrence of ice-off), inverse stratification was still detectable between 0.1 and 0.5 m. It took an additional 15 d for this stratification just below the decaying ice cover to disappear on 22 April 2008, and the ice-off date estimated using the 0.1 m temperature sensor was within 1 d of the observed ice-off date

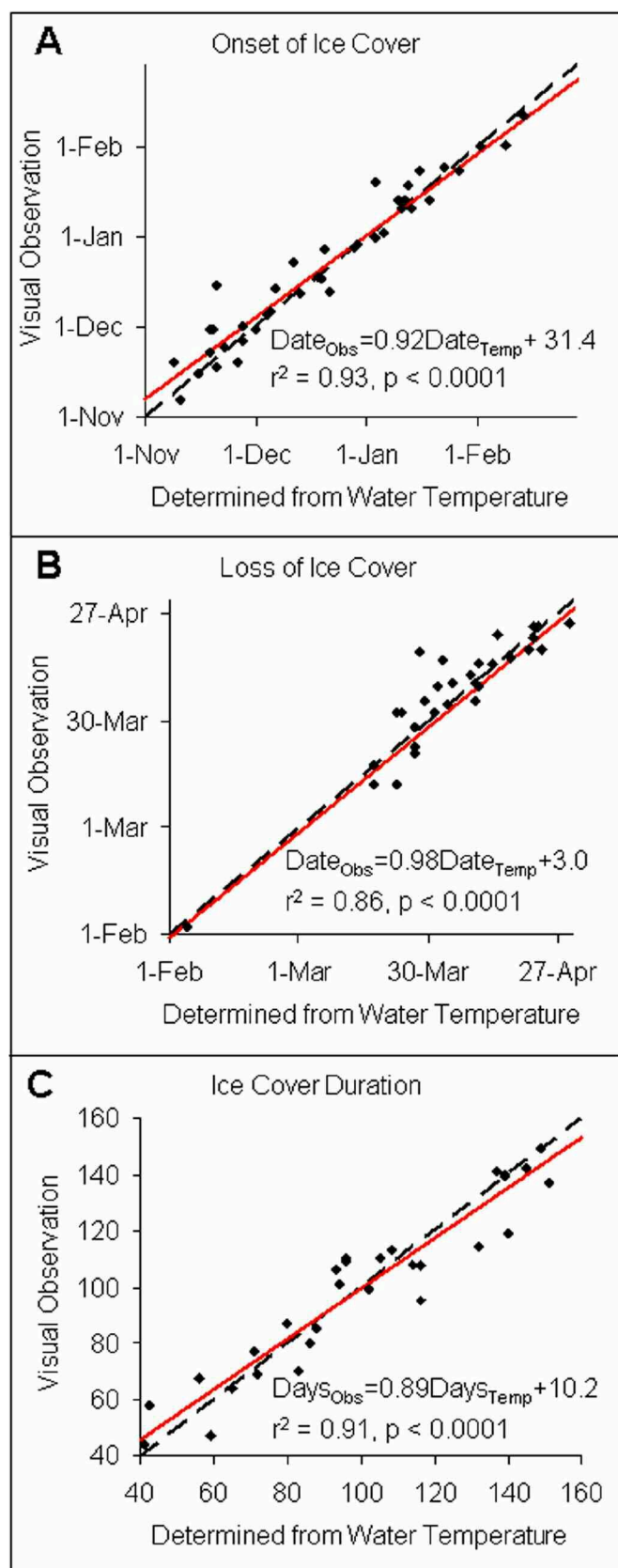


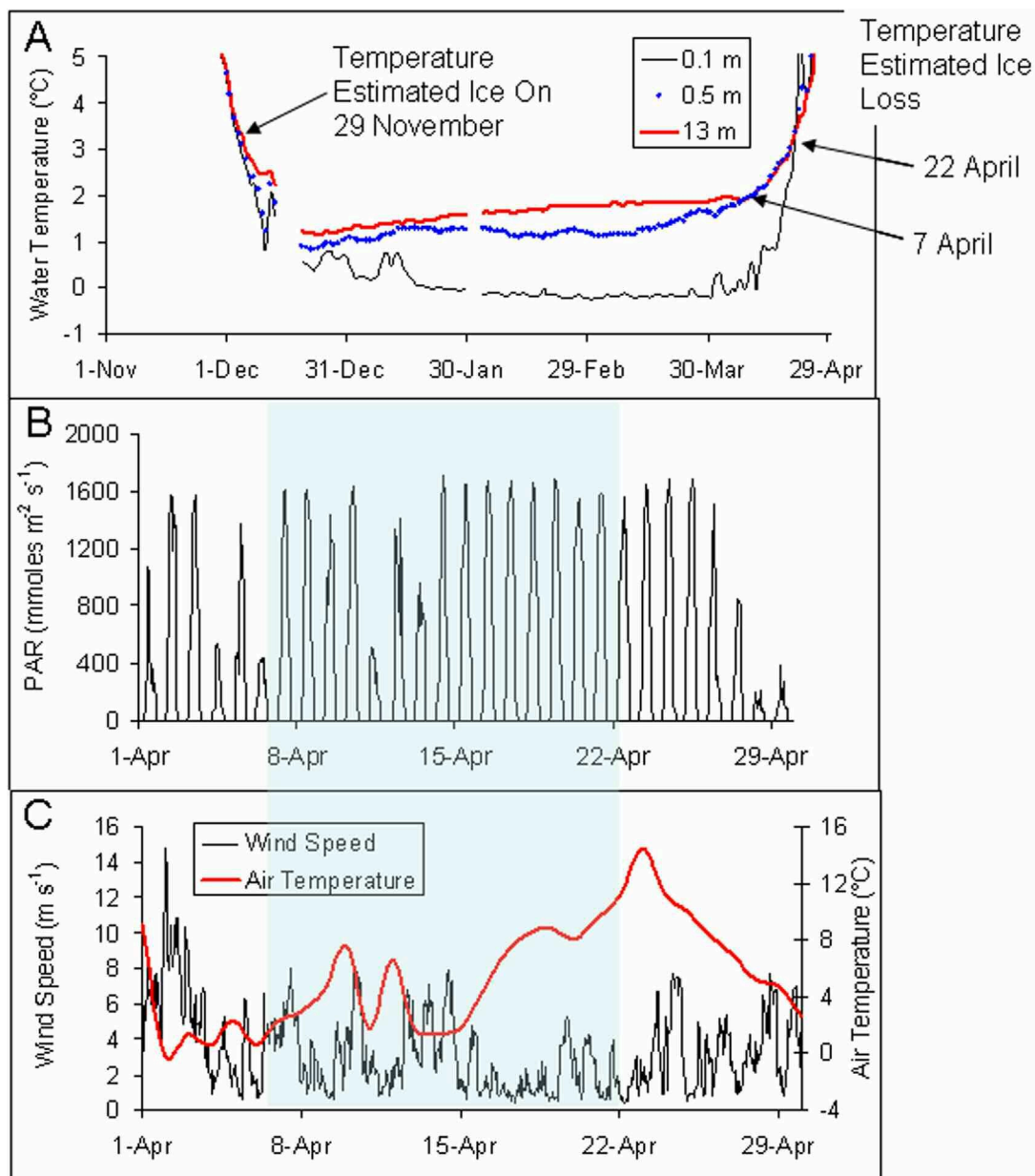
Fig. 2.

(Table 1). Estimates of land snow cover in the vicinity of Lake Sunapee (<http://www.nohrsc.noaa.gov>) suggest that snow depth ranged between trace levels and 5 cm on 4 April 2008, and that the area was completely free of snow by 10–11 April 2008. It has been previously documented (Kelley 1997) that in the absence of snow, solar radiation passing through the ice will lead to warming and convective mixing below the ice. This is apparently what happened in Lake Sunapee (Fig. 3). As the water temperature at 0.1 m increased to above 0°C, only the upper 0.5 m of the water column remained inversely stratified. The remaining water from 0.5 m–13 m warmed over time and remained isothermal, suggesting convective mixing. The period when the lake was isothermal in all but the upper most 0.5 m is shown in Fig. 3A, and detailed meteorological data from this time are shown in Fig. 3B–C. During this time, it was unusually sunny and calm. Solar radiation levels were often near the maximum that could be expected, and the air temperature was well above freezing. Wind levels during this period were relatively low, which allowed the ice cover to decay slowly.

In addition to Lake Sunapee, there are nine additional data sets in Table 1 that contain data from both a shallow (0.01–0.2 m) sensor and a sensor at 1 m depth. The differences in the timing of ice-on and ice-off as estimated using the two different surface sensor depths are shown in Fig. 4. These data show that estimation of the timing of ice-on is not affected by the depth of the upper sensor, and further suggest that the timing of ice-off can at times be underestimated using a sensor at 1 m depth. For the data in Fig. 4, the date of ice-off would be underestimated by more than a week in 3 of 10 cases.

The underestimation of the date of ice-off does not always occur as shown by Fig. 4, presumably since ice-off, especially in large lakes, often occurs during windy conditions that lead to more rapid break-up and vigorous mixing. There are many cases in Table 1 where the date of ice-off closely matches visual observations, even though a shallow surface sensor was not used. However, the phenomenon illustrated by Figs. 3 and 4 can explain the apparent bias toward earlier ice-off dates in the temperature-based estimates shown in Fig. 2B. For this reason, we recommend that, whenever possible, a sensor be deployed at a shallow depth so that it will be frozen into the ice. For all lakes for which 0.01–0.2 m data were available (Table 2), this shallow sensor was used to calculate the temperature-based ice phenology estimates in Table 1. Biases, such as those illustrated in Fig. 4, therefore, only exist in Table 1 for cases where the upper sensor was at a deeper depth (0.5–3.0 m).

A second source of uncertainty in both observational and temperature-based estimates of ice cover is related to the fact that lakes (particularly large lakes) do not always completely freeze over or become ice free during a short time interval. In some cases, the onset or loss of ice may occur over a period of

**Fig. 3.**

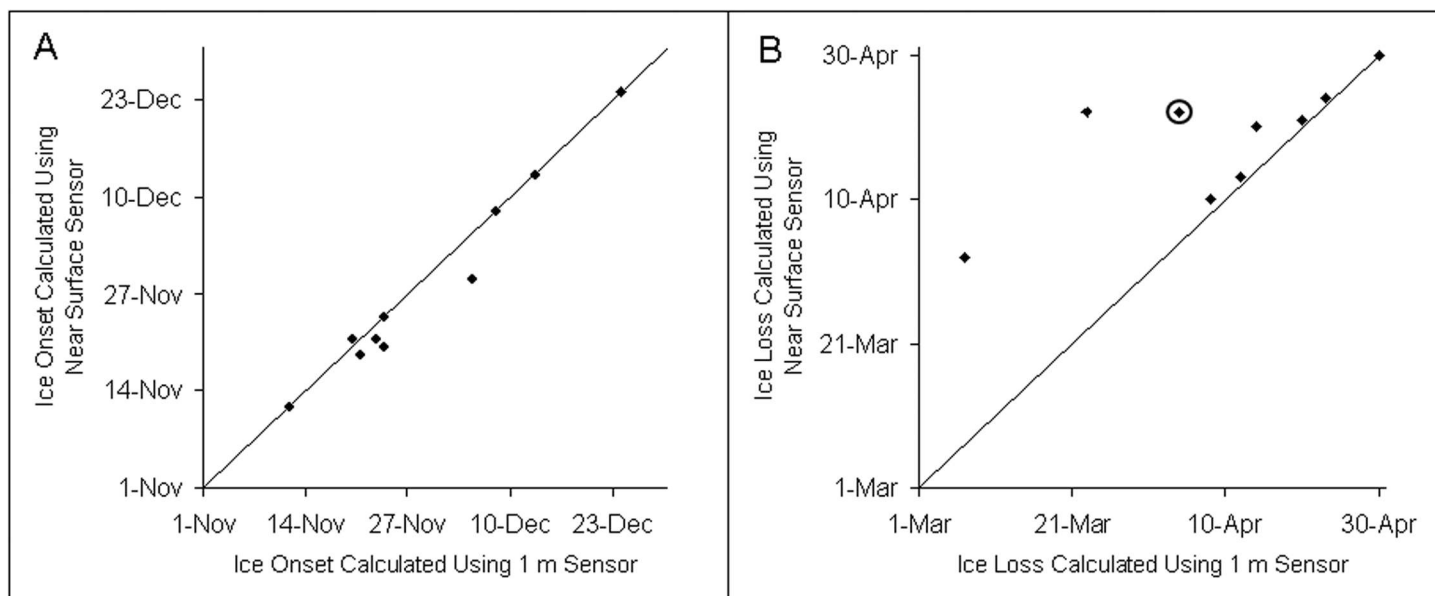
a week or more, adding uncertainty to observer-based estimates because there may be differences in the perception of what constitutes ‘complete’ ice cover, or in the case of temperature-based estimates, uncertainty may result from the placement of the sensors relative to the location of ice and open water. Such uncertainty must account for some of the variations between temperature- and observer-based estimates of ice cover in Table 1. To reduce measurement uncertainty in large lakes, or lakes that are known to freeze unevenly, we would suggest deploying multiple measurement buoys.

Utility of temperature-based estimates of ice cover

Verification of the temperature-based ice phenology estimates is difficult because the data used for comparison are

based on human observations, which in themselves may be in error because of differences in perception, or more likely, differences in the frequency of measurement and availability of dedicated observers. Our results (Fig. 2) show that the temperature-based estimates are comparable with observer-based estimates, although at times there can be discrepancies between the two. It would not be appropriate to call such discrepancies errors in either measurement technique, because neither temperature-based nor observer-based estimates can be considered to give true measures of the timing of ice-on and ice-off, as both are subject to error.

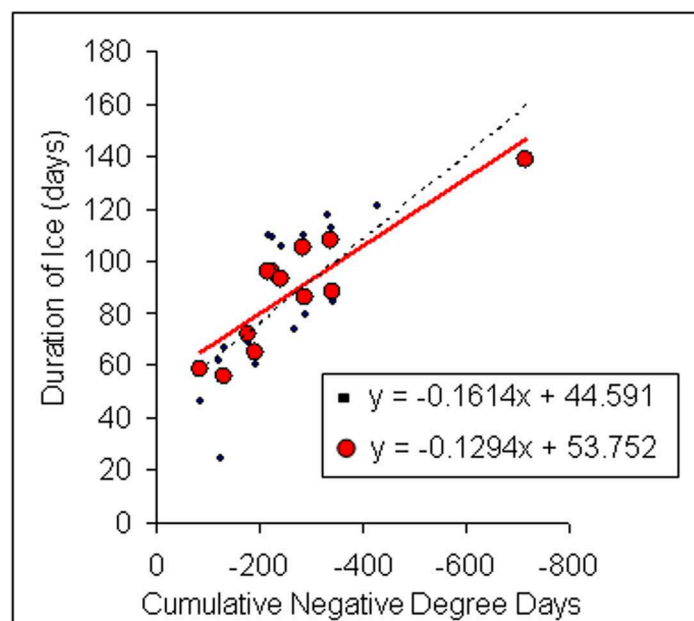
The value of the automated temperature-based estimates can also be judged by their ability to show the same long-term

**Fig. 4.**

trends in ice phenology that have already been shown to exist in observer-based estimates. If measurements based solely on water temperature are able to produce the same trend as data collected by more labor-intensive visual observations, this would clearly indicate that the proposed temperature-based method has practical use. To test this assumption, we made use of data collected from Lake Erken and examine trends in duration of ice cover and its relationship to measurements of air temperature made at the same site over the time period when both temperature-based and observer-based estimates of ice duration were available. The relationship between ice cover duration and cumulative negative degree days (Fig. 5) is well described using either temperature-based or observer-based estimates of ice cover. Analysis of covariance found that the linear trend lines associated with the two data sets could not be statistically distinguished from one another ($P \sim 0.5$). This example clearly verifies the value of the temperature-based estimates of ice cover duration, since estimation of ice cover duration by either method would produce essentially the same trend with air temperature.

Comments and recommendations

A simple method to automatically determine the timing of ice-on, the timing of ice-off, and the duration of lake ice cover is described that makes use of water temperature measurements. The temperature-based estimates were compared with observation-based estimates for 43 winter seasons using data from 10 lakes and reservoirs. RMS differences between the two estimates calculated over the entire data set were 7.1 d for the timing of ice-on, 6.4 d for the timing of ice-off, and 10.0 d for the duration of ice cover. Compared with observer-based estimates, temperature-based estimates of the date of ice-off

**Fig. 5.**

can at times show a bias toward earlier dates. This is likely a consequence of convective mixing under the decaying ice cover, and the bias can be eliminated by using a shallow sensor that freezes into the ice. Ice phenology estimates made by the proposed temperature based method show similar differences to observations as estimates based on satellite remote sensing (Wynne et al. 1996), however many of the lakes studied here would be too small for measurement by remote sensing.

The proposed method could be used in regional studies of large numbers of lakes to better document temporal and spa-

tial changes in ice phenology. This would lead to a better understanding of the factors that influence variations in lake ice cover, and would allow long term trends in lake ice cover to be examined in the context of more robust estimates of local and regional variability.

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