LIMNOLOGY
and
OCEANOGRAPHY: METHODS

Limnol. Oceanogr.: Methods 00, 2015, 00–00

doi: 10.1002/lom3.10083

Lake ice measurements from soil water content reflectometer sensors

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Abstract

Lake ice depth provides important information about local and regional climate change, weather patterns, and recreational safety, as well as impacting in situ ecology and carbon cycling. However, it is challenging to measure ice depth continuously from a remote location, as existing methods are too large, expensive, and/or time-intensive. Therefore, we present a novel application that resolves size, cost, and automation issues using commercially-available soil water content reflectometer sensors from multiple manufactures. Analysis of sensors deployed in an environmental chamber using a scale model of a lake demonstrated accurate measure of the change in ice depth over any time period to within 1 cm, through sensor response of liquid-to-solid phase change. A robust correlation exists between volumetric water content in time as a function of environmental temperature and ice growth. This relationship allows us to convert volumetric water content into ice depth. An array of these sensors can be used in lake or river settings to create a temporally high-resolution ice depth record, which fills in a needed gap for ecological or climatological studies as well as increasing public recreational safety.

Lakes are an important component of the Earth's climate system and climate change impacts to lakes include alterations to both physical and biological processes throughout all seasons (Magnuson et al. 1997). Long term winter records of lake and river ice cover have been compiled from Canada (Duguay et al. 2006), Finland (Korhonen 2006) and the Northern Hemisphere (Magnuson et al. 2000) and show shorter ice coverage periods. Global climate modeling efforts show that lakes have strong connections to climate at the local (Deng et al. 2012) and regional scales (Strong et al. 2014). Several lake-atmospheric observation data sets are available now (Schertzer et al. 2003; Lee et al. 2014), but year round observational data including ice thickness from lakes that freeze are needed to better parametrize models.

Winter lake ice cover has important implications beyond just local and regional climate, such as water quality, ecology, and human use. Ice cover reduces surface energy and gas exchange. The partitioning of sensible and latent heat fluxes by lakes impact the local atmospheric surface layer's stability (Nagarajan et al. 2004) and can have effects at the regional scale (Rouse et al. 2005). Ice cover can lead to anoxic and low-light conditions, both of which can impact phytoplankton and their linked food-chains (Vanderploeg et al. 1992). Man-made structures can be damaged by ice expansion or drift and recreational activity safety depend on ice cover and thickness. With nearly 2,000,000 people participating in ice fishing annually in the United States (United States Department of the Interior and Wildlife Service 2013) and the majority of deaths being attributed to thin lake ice (Barss 2006), ice thickness measurements disseminated to the public in near-real-time would greatly improve the safety conditions of recreational ice activities.

However, measurements of lake ice is challenging due to the physical properties of the water-liquid boundary. Several types of under-ice measurements are possible including subsurface solar radiation data which require knowledge of how ice conditions that change radiative transfer throughout the winter (Bolsenga 1978) and moored sub-surface sonar sensors which requires temperature dependent speed of sound corrections, (Melling et al. 1995; Brown and Duguay 2011). Recent advances in using X- and Ku-band radar is promising, but requires information or assumptions on ice conditions (Gunn et al. 2015), in which in situ data is still needed. One of the larger datasets from oceanographic submarine sonar data and the National Snow and Ice Data Center (2006) does not apply to lake systems. Buoys have been used in the Arctic Ocean, but larger-scale deployment is limited by production cost of the buoys themselves (Polashenski et al. 2011). Weekly time-series data can be collected by hand, but is labor intensive and can miss temporal processes between

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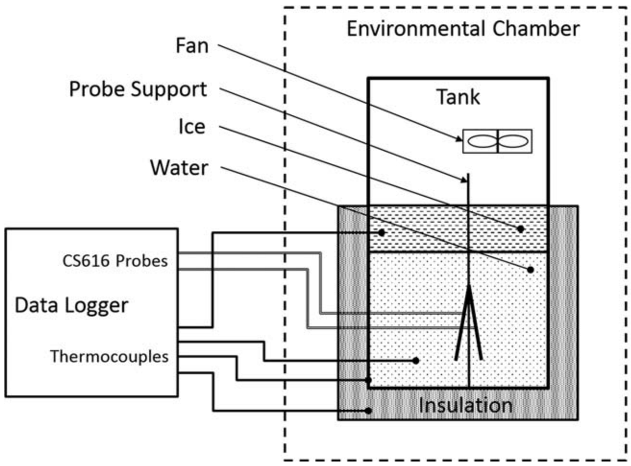

Fig. 1. A conceptual figure of the experimental design using the simulated lake in a Tenney environmental chamber.

Fig. 2. Photo of the inside of the Tenney environmental chamber in between experimental runs showing the insulated polyethylene tank.

collections, including key parameters like seasonal ice maximum and dangerous thin ice (Sleator 1995). Ice can also be modeled using thermodynamic properties and optical satellite data to calibrate models (Liston and Hall 1995; Wang et al. 2010). While short-scale temporal modeling is possible, models are sensitive to atmospheric wind speed, the condition and depth of snow on top of the ice, surface albedo and radiation fluxes and uncertainties limit to model accuracy. Recently, to measure ice thickness Cui et al. (2015) demonstrates new methodology that utilizes in situ measurements of electrical resistance to model ice thickness. This approach allows a direct measurement of the ice sheet, but requires a temperature-dependent correction and a complex, custom build sensor array.

Here, we demonstrate how commercially-available, relatively low-cost and low-power soil water content reflectometer sensors can be repurposed as a tool to measure lake ice. These sensors traditionally measure the volumetric water content of soils using time-domain reflectometry and hence are able to detect the phase change of water. Their temporal response, cost, and durability make them a cost effective way to record sub-hourly ice thickness directly with minimal manual labor and measurement uncertainties that are associated with the other ice thickness methods. We discuss operational characteristics of the sensors as well as the temperature relationship of ice formation and melt in a lab setting.

Methods

Experimental setup

We built a model to simulate a lake freezing only from the surface down, instead of freezing inwards from all sides (Fig. 1). The molded polyethylene 46 cm × 10 cm × 46 cm tank (United States Plastic Corp., Lima, Ohio) was wrapped around the sides and bottom with fiberglass insulation 4.25 cm thick on the sides and 8.5 cm thick on the bottom to limit heat transfer through those surfaces.

Water content reflectometers (Campbell Scientific CS616, Logan, Utah) operate by generating an electromagnetic signal and then measuring the signal attenuation and travel time down the probe length and back. Normally used in soil, changes in signal strength and travel time is used to calculate soil volumetric water content based on soil type standard calibrations. When used in the simulated lake, the sensors measure water phase change between liquid and solid states, resulting in a lower volumetric water content reading as the ice solidifies around the sensors.

Two of these sensors were attached to a wooden dowel with the sensors placed on the bottom on either side of the dowel. A wooden dowel was used as it would conduct less heat, helping to ensure a level ice layer. The dowel was placed upright in the center of the tank and secured so that it would not tilt. The tank was then filled with tap water until the top sensor's prongs had been covered, roughly 10 L. Thermocouples (Omega; Type T Copper-Constantan) were placed in the side insulation, both 10 cm from the bottom of the tank, as well as in the water, one at 1 cm off of the bottom of the tank the other 1 cm below the water surface. This was done to measure water temperatures without influence of the tank sides.

The tank was placed in a programmable environmental chamber (Tenney Versa Tenn V, Tidal Engineering, Randolph,

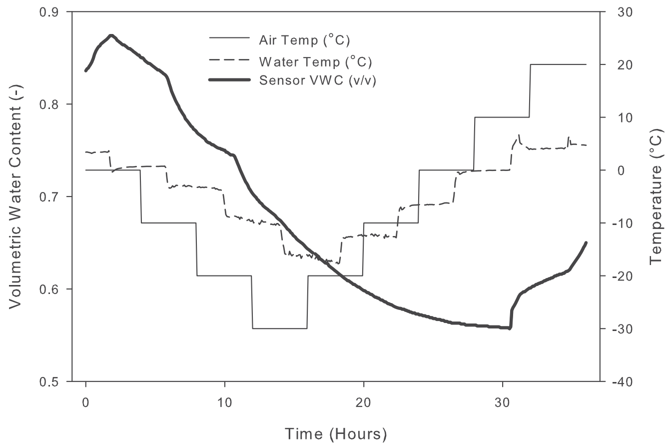

Fig. 3. Illustrative time-series showing a temperature step-function that highlights the time delay in water temperature change and sensor response. A small amount of ice was left at the start of the experimental run to show both thin and thick ice sheet melting.

New Jersey) (Fig. 2). The data logger (Campbell Scientific CR10X, Logan, Utah) was stored outside of the chamber and collected volumetric water content data at 30-min intervals. The tank was frozen twice at −30°C, three times at −20°C, and once at −10°C. After every experiment the ice growth was removed, measured with a ruler and then melted before the next experiment began, with one melting experiment at 20°C and one at 30°C. Also, the tank was held at a constant temperature of 0°C once. The length of each varied between 4 h and 18 h.

Several experimental runs were needed to determine the operating characteristics of the environmental chamber and tank. The final design is shown in Fig. 1 and was a semi-filled tank with insulation covering part of the sides and a fan to circulate air in the headspace above the waterline. A lower volume of water in the tank lead to faster experimental runs as less thermal mass needed to change temperature.

In a smaller 7.5 L tank, we conducted a second set of experiment to test the effects of sensor probe deformation and ion concentration variation on uncertainty in ice thickness-SWC relationship. For ionic concentration, a simple solution from 60 g of sodium chloride was used. In this modified set up the effects of bending the rods, cutting them, and placing a solid object between them were examined as well. This tank was also used to compare two water content reflectometers (10HS Soil Moisture Smart Sensor) from a second manufacture (Decagon Devices, Pullman, Washington) using a HOBO data logger (Onset Computer Corporation, Bourne, Massachusetts).

Data analysis

The relationship of CS616 sensors' soil water content response to ice depth was linear, thus require only two calibration coefficients, an intercept for maximum depth and sensor ice sensitivity. When the probes are fully covered in ice, the sensor response is 0. Thus, we can derive ice depth using the following equation, where *a* is the resting volumetric water content reading, *m* is the slope and *x* is the sensor's measurement, along with the 30 cm length of the probe.

$$0=am+30$$

$$y=\begin{cases} 0, & if\ \ x \geq a \\ mx(t)+30, & if\ \ 0 < x < a \\ 30, & if\ \ x \leq 0 \end{cases} \tag{1}$$

We assume *y* is a linear function of temperature.

The response of the sensor with no ice varies by sensor, and thus require sensor specific calibration to derive resting volumetric water content in liquid water with no ice. Tests so far found this value to be dependent on inherent characteristic and physical properties of the probes, including any deformation or bending. For Sensor "1", the resting volumetric water content was 0.74 in soil volumetric fraction, resulting in Eq. 1 where *m* is the slope at which ice forms.

$$0=0.74m+30, \tag{2}$$

When solved we get the piece-wise function (Eq. 2) where *x* is the volumetric reading from the sensor, −40.75 was found by solving Eq. 1 for *m*.

$$y=\begin{cases} 0, & if\ \ x \geq 0.74 \\ -40.54x(t)+30, & if\ \ 0 < x < 0.74 \\ 30, & if\ \ x \leq 0 \end{cases} \tag{3}$$

Sensor "2" had a different resting volumetric water content reading in room temperature liquid water of 0.96. The same method of converting water content to ice depth was applied. Changes to this calibration equation were needed when converting between volumetric water content and ice depth for Decagon sensors due to shorter (15 cm) probe length and different resting temperatures. Sensor accuracy and precision information were based off of the manufacture's specifications.

Results

Twenty freezing and melting tests were run in the environmental chamber. A photo of one run is shown in Fig. 2. The lowest recorded air temperature was −30°C and the lowest water temperature was −15°C, while the highest air and water temperature was 20°C. The chamber was run for longer periods of time at warmer conditions to ensure complete ice melt between runs, and also allowed temperature equilibrium throughout the volume. As designed, ice formation was primarily top down with ice growth along the side and bottom not significant under test runs of less than 12 h. Longer

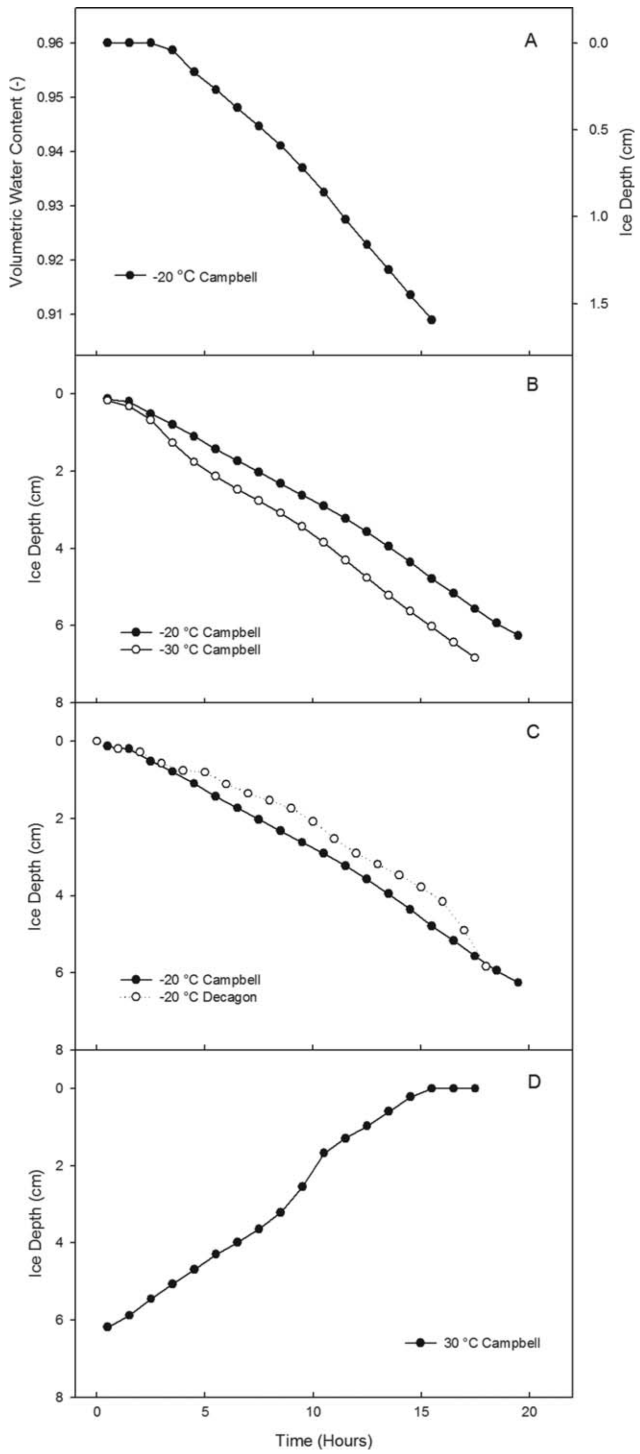

Fig. 4. Conversation is shown between typical sensor readings of volumetric water content to the calculated ice depth values (A), ice sheet growth at −20°C and −30°C (B), Campbell and Decagon sensors at −20°C (C) and ice sheet melt at 30°C (D).

runs at colder temperatures caused ice growth along all sides of the tank due to insulation limitations, creating complex and unrealistic conditions.

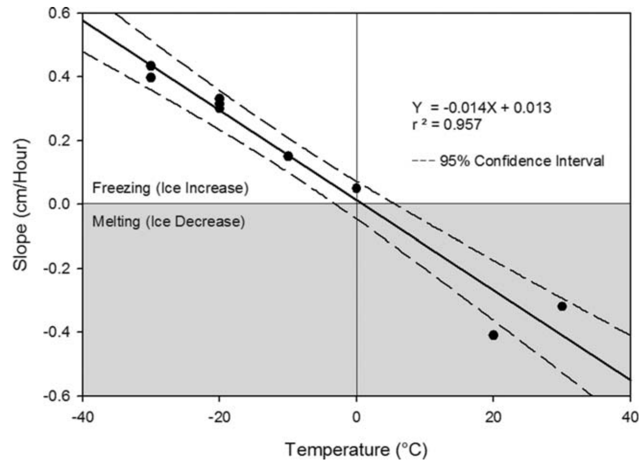

Fig. 5. The slope or rate of ice growth for individual runs is plotted as a function of temperature. The regression slope and r^2 value of the regression is shown, along with the 95% confidence interval. Shaded areas correspond to ice sheet melting.

An environmental run of a 4 h temperature step function between −30°C and 20°C is shown in Fig. 3 to highlight sensor performance. A small amount of ice (2 cm) was left from the previous run to show volumetric water content sensor response is similar between melting of a surface lay of ice and melting ice at depth. There is a time lag between air and water temperature changes, due in part to insulation of the tank, and water temperatures start above 0°C. With a decrease in temperature, a clear response from the sensors showing 0.3 cm of ice growth in 15 min is noted. When temperatures increase from −30°C, the ice layer was 12 cm thick and little new ice growth is noted. When water temperatures are positive, the sensor shows 0.7 cm of ice melt over 15 min.

The derived relationship between volumetric water content and ice depth is shown in Fig. 4a, with this environmental run starting with above freezing water and no ice. After 3 h, water temperature cools to below freezing and ice growth begins. After the run, the ice layer was removed and measured to calibrate the sensors. Similar environmental runs were done at multiple temperatures (Fig. 4b) with 6 cm of ice growth taking 3 h longer at −20°C air temperature as compared to −30°C.

The comparison between Campbell and Decagon sensors, both at −20°C, is shown in Fig. 4c. While there is a difference in insulation as the Decagon sensors where tested in the smaller tank, there is the same amount of ice growth after 18 h. To test melting conditions, several environmental runs were done with an existing ice sheet in place. Figure 4d shows a run at 30°C.

The expected linear relationship between the rate of ice change (freezing or melting) and temperature between −30°C and 30°C is shown in Fig. 5. Areas of melting or a decrease in ice thickness is shaded. The r^2 value of the relationship was high and the 95% confidence interval overlaps the zero temperature, zero ice change point. Probe deformation ionic concentration experiments both changed water content readings by 1–2%.

Discussion

Comparison to other ice thickness measurements

Current measurements of lake ice thickness are either labor intensive, sensitive to changing ice conditions or cost prohibitive, while ice thickness is an important ecological and climatological measurement that is often overlooked in favor of only measuring the timing and extent of ice cover. We successfully showed in a lab experiment that using soil water content sensors is a precise and cost effective system to measure ice depth. Sensors from both Campbell Scientific and Decagon Devices performed similarly, with the only noted difference between the two being probe length and compatibility with logger systems. The system can be deployed seasonally or left on the body of water year-round, either as a stand-alone sensor or as part of a water quality or water level measurement suite.

In comparison to other electrical resistance type methods, here the entire rod is integrated over the measurement so air pockets in the ice, liquid lens, or ice cracks are not a problem unlike in other ice depth measurements and sensor soil water response precision instead of placement of electrodes determines the maximum ice depth precision. Also of note is that, ice thickness can be measured at the sub-hourly scale throughout the entire winter, previously only possible with custom built buoys or electrical resistance sensors. However, sensor resting water content is quite variable between sensors (see section 4.2), and thus in situ calibration is recommended at least once per sensor to have a base reference point for Eq. 3.

Ice temperature information is needed to calculate ice thickness with other techniques. The electrical resistance sensors of Cui et al. (2015) require air, ice and water temperature measurements to correct resistance measurements before thickness is derived. The relationship between temperature and ice growth/decay shown in Fig. 5 is linear, matching the predicted analytical ice models for small ice sheet volumes with no insulating snow (Leppäranta 1993). This shows temperature corrections are not required for time-domain reflectometry sensors and that the need to measure environmental temperature of other techniques is eliminated. This has the results of reducing the complexity and error of the final ice thickness measurement.

The cost of the Campbell Scientific dataloggers that are compatible with their soil water content sensors start at \$1000, which could be cost-prohibitive, but Campbell Scientific soil water content sensors cost \$120 each. The cost of a pair of Decagon sensors to equal the same 30 cm probe length and a HOBO logger was \$600 total. Either option would be well over an order of magnitude less expensive than a comparable sub-surface sonar sensor which costs \$18,000.

Sensor limits and seasonal-scale errors

Thin ice sheets can be difficult to measure. With manufacture reported sensor accuracy of 2.5% percent for the Campbell Scientific CS616 probes and 3.1% for the Decagon sensors, this translates to ice thickness accuracy of 0.75 cm and 0.465 cm, respectively. Given that ice thickness can change relatively fast for thin ice sheets (Thorndike 1992), measurements may not be fully reliable until nearly a full centimeter of ice growth is present. For context, an ice thickness of 5 cm is typically given as a minimum threshold to the public for winter activity safety and a thickness of 10.1 cm is advised for ice fishing.

In testing, it was noted that the resting volumetric water content reading of the sensor was affected by the ion concentration of the water. Readings were changed by only 1–2% when a sodium chloride solution was used that was significantly higher than typically seen in the environment. This can lead to errors of 0.3 cm in ice thickness, but would require a large change in dissolved ion concentration under the ice, not just a high ion concentration. Except in rare cases, should not lead to systemic issues with the measurement. If this is a concern, collocating a dissolved ion measurement would allow for this effect to be corrected.

In potential cases of ice drift or heave deforming the sensor probes, another error of 1–2% in volumetric water content would lead to error of 0.3 cm in ice thickness. This is due to sensors being bent in a way that altered the proximity to nonwater solid objects, and hence the sensor's signal delay and attenuation. In our laboratory setup, bending the probes around the wooden support created an error of one percent in the measurement. Sensor location in the field is an important consideration if ice drift or heave is typical for that lake. Solid mounting on a structure that is resistant to ice damage (pier, bridge abutment or support) would remove this error.

Cumulative errors from changing water ion concentrations or probe deformations can be limited with proper care in selecting measurement locations. For measurements in difficult locations, these corrections can be addressed at the end of the winter season. A change in ice-free resting volumetric water content reading can be tested using prewinter and postwinter readings and corrections similar to snow depth measurements can be applied (Johnson and Marks 2004).

Conclusion

Currently there are few cost effective methods to directly measure ice cover and thickness. This work demonstrates how soil water content sensors can be repurposed to measure ice thickness without having to correct for environmental temperature and at shorter timescales than possible with most other methods currently used by the field. Response is linear from 0 cm up to probe length, with estimate precision of 0.1% and accuracy of 2.5% for the Campbell sensors and precision of 0.07% and accuracy of 3.1% for the Decagon sensors. Due to the change in travel time of a generated electromagnetic pulse from the sensor that captures the phase transition during ice grow/melt, the measurement is similarly robust and comparable to time-reflectance sonic sensors that measure changes in snowpack height during the cold season compared to a snow-free reference point. Individual sensors probes can be deformed by ice drift with minimal effect on the measurement. Despite sensor-specific calibration issues, this new sensor application allows the possibility of large-scale lake or river measurement networks in the future, with implications for safety, as well as environmental or climate change research.

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Acknowledgments

We would like to thank Jonathan Thom for assistance with the environmental chamber and Yost R. for early conversations about the ability of soil sensors to detect phase changes. This study was supported by the National Science Foundation (NSF) Atmospheric and Geospace Sciences Postdoctoral Fellowship Program (#GEO-1430396) and NSF Research Experience for Undergraduates (REU) supplement to the North Temperate Lakes Long Term Ecological Research program (NTL-LTER) (#DEB-0822700 and DEB-1440297).

Submitted 17 August 2015
Revised 20 November 2015
Accepted 4 December 2015

Associate editor: Paul Kemp