Cover letter

Dear Editor

Please see below a combined file including

1) response letter
2) revised manuscript

The response letter was given in such a format that the comments are text in black colour and our responses are given in red text.

The revised manuscript has considered all comments from reviewers. The changes are those text marked with yellow background.

Thank you for considering our manuscript to be published on ESSD.

Best regards,

Bin Cheng and co-authors.

Comments from first reviewer and responses from the authors

The paper as submitted represents a significant effort to measure and analyse long-term trends in Boreal Lake ice behaviours and the results are very relevant to ongoing monitoring of climate changes. The paper also details useful developments in the instrumentation used and the methods of analysis of the data the instruments produce.

This reviewer is an Engineer involved in the initial development of the instrumentation used and cannot comment on the metrological and climatological issues raise and analysed. Comments are limited to instrumentation matters only.

The work details a considerable programme of over a decade duration over which the SIMBA instrument has developed. The authors present advances made in the instrument itself and improved methods of deployment but more significantly is the presentation of results from a newly developed algorithm to process the SIMBA data. This is a major advancement in the use of the SIMBA device as to date the interpretation of results has been largely subjective human activity. The use of this algorithm now allows for a repeatable and consistent analysis of the considerable data set collected.

Specific comments on the text are as follows.

The SIMBA sensors are calibrated at a single point to remove large offsets in a very accurately controlled bath. The sensors have been shown to be very linear and so the largest source of error becomes the resolution of the sensors. The absolute accuracy is therefore in the region of the resolution plus the error in the water bath accuracy which is very small. The quoted +-0.01C is not possible and the accuracy more like +-0.0625C. The sensor drift over time is small and can largely be ignored.

Reply: Thank you to point out this error. We made correction accordingly. The new text read: The accuracy of the SIMBA thermistor sensor is ± 0.1 ºC, which is comparable with other type of thermistor string based IMBs (Richter-Menge et al. 2006).

Diffusivity is a transient measure of how heat is conducted away when a temperature change occurs (i.e. how cold to the touch something is). The SIMBA heating cycle is usually long enough for the temperature rise at the sensor to reach a steady state so is it not the thermal conductivity which dominates?

Reply: We modified the text to: The SIMBA heating cycle is usually long enough, often 60 or 90 s, for the temperature rise at the sensor to reach a steady state. Thermal conductivity determined how the heat is conducted away of the heated sensors placed in air, snow, ice and lake water. As a result, the SIMBA-HT profiles can greatly enhance the detection of the interfaces between air, snow, ice and water.

Really impressive plots!

Reply: Thanks

Overall this is a paper worthy of publication and represents an impressive and well executed effort at studying important phenomena.

Thank you for your positive comment on this work, we appreciate your great effort making this novel，compact and cost cutting instrument, which allow us to carry out sustainable field campaigns.

Comments from second reviewer and responses from the authors

This paper used a thermistor string-based snow and ice mass balance apparatus (SIMBA), which is a novel monitoring method for snow and ice thickness, to monitor the temperatures of air, snow, ice and water, and to get the snow and ice products applying a algorithm, finally to reveal the relationship between climate change and snow/ice thickness. Based on the decadal date sets, authors described the snow and ice temperature regimes, snow depth, ice thickness, and ice compositions as well as meteorological variables at the Finnish Space Centre. These decadal data sets provided firstly can also be used for numerical and satellite validation and can be comparable to the results obtained from other cold regions. So, it is important and interesting issue and is worthy of publication after some revisions. Some comments are raised as follows.

The paper is wrote well entirely. However, there are still some problems in English writing. Such as, "thermal heat conductivity" is suggested to be "thermal conductivity"; Please check "Figure 8" in Line 195 and "Figure 9" in Line 211. It is suggested to revise the English description entirely.

Reply: Thanks for your suggestions. We made corresponding corrections and the language of the entire manuscript has been checked carefully.

"Figure 8" in Line 195 should be "Figure3"
corrected

"Figure 9" in Line 211 should be "Figure4"
corrected

"thermal heat conductivity" in Line 194 modified to "thermal conductivity"
Done

In Lines 328-329, author described "….a decrease of FDD is expected to result in less formation of columnar ice". Please explain why.

To be more precise, in the revised manuscript, we change FDD and TDD to AFDD and ATDD, respectively. So AFDD is the accumulated freezing degree day, and ATDD is the accumulated thawing degree day. So FDD is a measure of how cold the day is and AFDD is a quantitative estimation on how cold a winter is. Based on classical Stefan's law (1891), i.e., ice growth is proportional to the accumulated freezing degree day (AFDD). A decrease of AFDD means the winter is less cold, so the columnar ice (ice frozen due to freezing of lake water) is reduced. To avoid confusion, we updated the figure caption: Figure 11. The seasonal accumulated negative freezing degree day (AFDD) and positive thaw degree day (ATDD) during the observation period (2009/2010 – 2019/2020).

In Lines 381-383, the increase of air temperature in winter season is highly correlated with seasonal total accumulated precipitation. Please address its reasons.

In Scandinavia, warm winter weather is typically associated with higher precipitation rates. This is because they are due the same reason. Transient cyclones transport warm, moist air masses to Scandinavia. Without transient cyclones, colder and drier winter weather would prevail in the region. We added two sentences in the conclusion to emphasis this important issue.

In Lines 388-390, the seasonal accumulated FDD is reducing, suggesting reduced formation of columnar ice and, hence, a smaller role of air temperature in controlling the ice thickness. It is a little partial. In cold regions, air temperature is still the dominant factor controlling the ice thickness. Maybe other factor, such as precipitation in winter, play an important role in ice thickening. Please offer the accurate description.

The original description was not very accurate. We were meant to say that the role of air temperature on lake ice formation is getting smaller (because the general warming trend of air temperature in the polar region) rather than the role of air temperature is small. The air temperature is still the number one factor affect ice formation. So, the new sentence is:

Because of the air temperature increase, the seasonal AFDD reduces. This results in a decreasing impact of below-zero air temperatures on lake ice growth during the freezing season, as the growth of columnar ice is reduced. Simultaneously, the role of precipitation on total ice formation is enhanced because snow-ice and superimposed ice contribute to an increasing fraction of the total ice thickness.

Inter-annual variation of lake ice composition in European Arctic: observations based on high-resolution thermistor strings

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Abstract

Climate change and global warming strongly impact the cryosphere. The rise of air temperature and change of precipitation patterns lead to dramatic responses of snow and ice heat and mass balance. Sustainable field observations on lake air-snow-ice-water temperature regime have been carried out in Lake Orajärvi in the vicinity of the Finnish Space Centre, a Flagship Supersite in Sodankylä in Finnish Lapland since 2009. A thermistor string-based snow and ice mass balance buoy called "Snow and ice mass balance apparatus (SIMBA)" was deployed in the lake at the beginning of each ice season. In this paper, we describe snow and ice temperature regimes, snow depth, ice thickness, and ice compositions retrieved from SIMBA observations as well as meteorological variables based on high-quality observations at the Finnish Space Centre. Ice thickness in Lake Orajärvi showed an increasing trend. During the decade of data collection: 1) The November-May mean air temperature had an increasing trend of 0.16º C/year, and the interannual variations were highly correlated ($r = 0.93$) with the total seasonal accumulated precipitation; 2) The maximum granular ice thickness

ranged from 15 to 80% of the maximum total ice thickness; 3) The snow depth on lake ice was not correlated (r = 0.21) with the total precipitation. The data set can be applied to investigate the lake ice surface heat balance and the role of snow on lake ice mass balance, and to improve the parameterization of snow to ice transformation in snow/ice models. The data are archived at https://zenodo.org/record/4559368#.YIKOOpAzZPZ (Cheng et al., 2021)

1. Introduction

The rapid climate warming in the Arctic (Box et al., 2019; Przybylak and Wyszyński, 2020) has also affected lakes, in particular lake surface temperatures and lake ice phenology (Woolway, et al., 2019). In the Northern Hemisphere, the lake ice season has become shorter and lake ice has become thinner, and these trends are projected to continue throughout the 21st century (Sharma, et al., 2019). Lakes are important in the Earth system, as they can adjust local climate (Brown and Duguay, 2010), and affect the environment through interactions among physical, hydrological, biological, and chemical processes (Leppäranta, 2010).

Observations on snow depth and lake ice thickness are needed for (a) monitoring of climate variability and trends (Filazzola et al., 2020), (b) practical applications, such as use of lake ice for winter fishing, transport, and recreational activities (Leppäranta, 2015), and (c) to provide initial conditions for operational forecasting (Anderson et al., 2018). Snow depth and lake ice thickness can be measured manually. For example, in Finland, lake ice thickness is measured via manual drilling in a single location in 45 lakes with ten-day intervals throughout the ice season. However, this requires a lot of manpower, and accordingly does not allow collection of time series with a better spatial and temporal resolution. During recent decades, the number manual observations has strongly declined in many countries (Duguay et al., 2006). Satellite remote sensing yields information on lake ice cover (Wu et al., 2021) and snow/ice surface temperature (Cheng et al., 2014) with a sufficiently high spatial and temporal resolution. Kang et al., (2014) introduced a method to derive lake ice thickness from coarse resolution (~10 km) passive microwave data over large lakes in Canada. However, the transferability of the method to sub-pixel scale lakes has not been investigated. SAR polarimetry has shown some promise in retrieving ice depth over rivers (Mermoz et al., 2013); as fully polarimetric data is not to date widely available from existing SAR sensors extensive testing and application of the method for lakes is currently lacking.

The SIMBA data set is potentially highly relevant for the development of land applications for planned and existing passive microwave satellite sensors, such as the Copernicus Imaging Microwave Radiometer (CIMR), new Metop multichannel radiometer sensors of EUMETSAT, ESA SMOS, NASA SMAP and Chinese sensors. Due to the inherent coarse resolution of these sensors (tens of kilometers), a key issue is to acquire combined simultaneous data representing various processes in lakes, in addition to surrounding land areas. As such, the SIMBA forms an integral part of the FMI sensor network in Sodankylä.

Thermistor sting-based snow and ice mass balance apparatus (SIMBA) have been applied for more than a decade to measure snow depth, ice thickness and temperature profile from air through snow and ice to water (Jackson et al., 2013). Most of SIMBA have so far been deployed in Polar sea ice (Lei et al., 2018), but also lake ice has been studied (Cheng et al., 2014; Wei et al., 2016). In this paper we describe SIMBA observations from an ongoing program that started in Lake Orajärvi in northern Finland in 2009. Supporting meteorological observations from Finnish Meteorological Institute Arctic Research Centre (FMI-ARC) are also presented. The objectives of the SIMBA program were

- to evaluate the cost-effectiveness of SIMBA buoys in a remote lake environment
- to monitor climate variability and change as reflected in snow depth as well as lake ice thickness and composition
- to investigate (a) atmospheric forcing on lake ice growth and melt, (b) the role of snow on lake ice mass balance via formation of superimposed ice due to refreezing of melt water and rain and formation of snow ice due to flooding under a heavy snow load, and (c) the role of granular ice in lake ice phenology
- to develop better parameterizations of snow-to-ice transformation in numerical snow/ice models.

2 Observation

2.1 Sodankylä supersite

The SIMBA program at Lake Orajärvi is a component of the FMI Sodankylä supersite. The Finnish

Meteorological Institute's Arctic Space Centre (FMI-ARC) in Sodankylä (67.367 °N, 26.629 °E), Finland, is a super-observation site where various Earth observations (upper-air chemistry and physics, atmospheric column measurements, snow and soil hydrology, biosphere-atmosphere interaction) and ground truth measurements for satellite calibration-validation are carried out continuously (Fig.1). The site is equipped with comprehensive in situ and remote sensing instrumentation placed in the forests, wetlands and freshwater bodies, which are the main landcover types in the area. In this paper we focus on the cryospheric *in situ* observations of snow cover and lake ice as well as meteorological parameters.

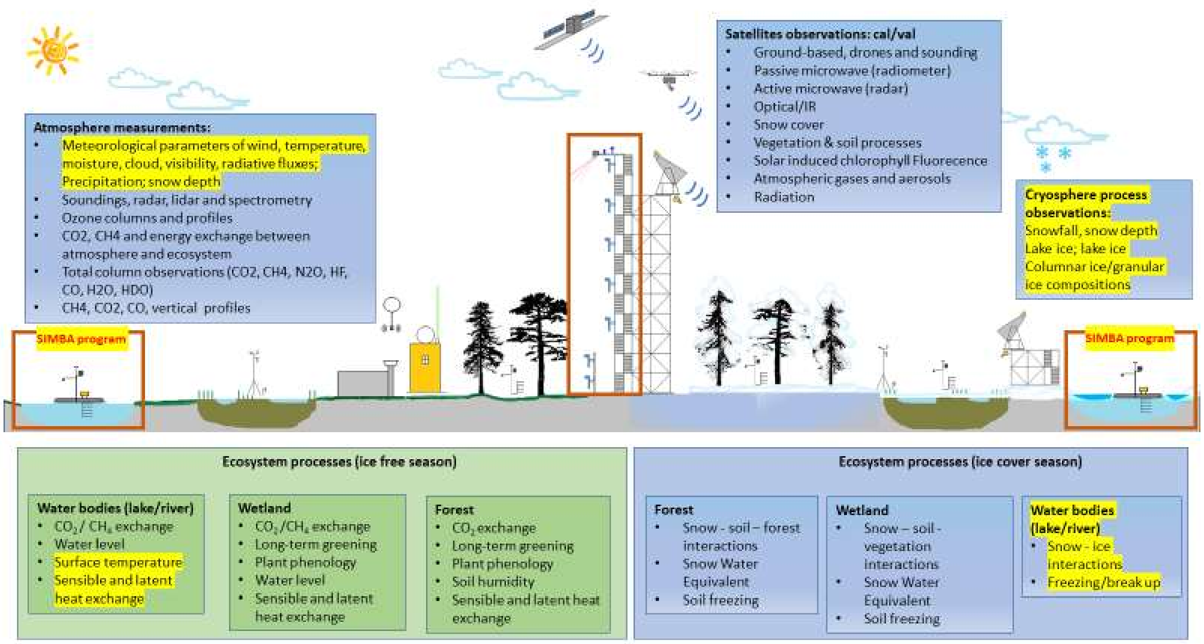


Figure 1. Schematic diagram of the FMI-ARC supersite observational systems at Sodankylä. The original diagram is at https://litdb.fmi.fi/. The frames in red and text with yellow background describes the measurements addressed in this paper.

The sub-Arctic climate and the geographic location between continental and marine climate zones result in a high inter-annual, seasonal and synoptic-scale variation in local weather conditions, enabling development of very different kinds of snowpack structures on land (Tikkanen, 2005) and snow/ice composition on lakes (Cheng et al., 2014). Lake Orajärvi is a boreal medium-sized lake located in Sodankylä municipality in the in the eastern Lapland. The lake has a surface area of about 11 km^2 with an average depth of 4.4 m and a maximum depth of 11 m close to the southern shore of the lake (Fig. 2a). The estimated water volume in the lake is 0.0485 km^3, and the shore length is 28 km. The lake surface elevation is 182 m above sea level. The ice season typically starts in November and lasts until May. The first snowfall typically occurs in late October, but the snow may melt during warmer autumn days. The seasonally permanent winter snow accumulation usually starts between mid-November and early-December. Snow is present on the lake ice surface every winter season.

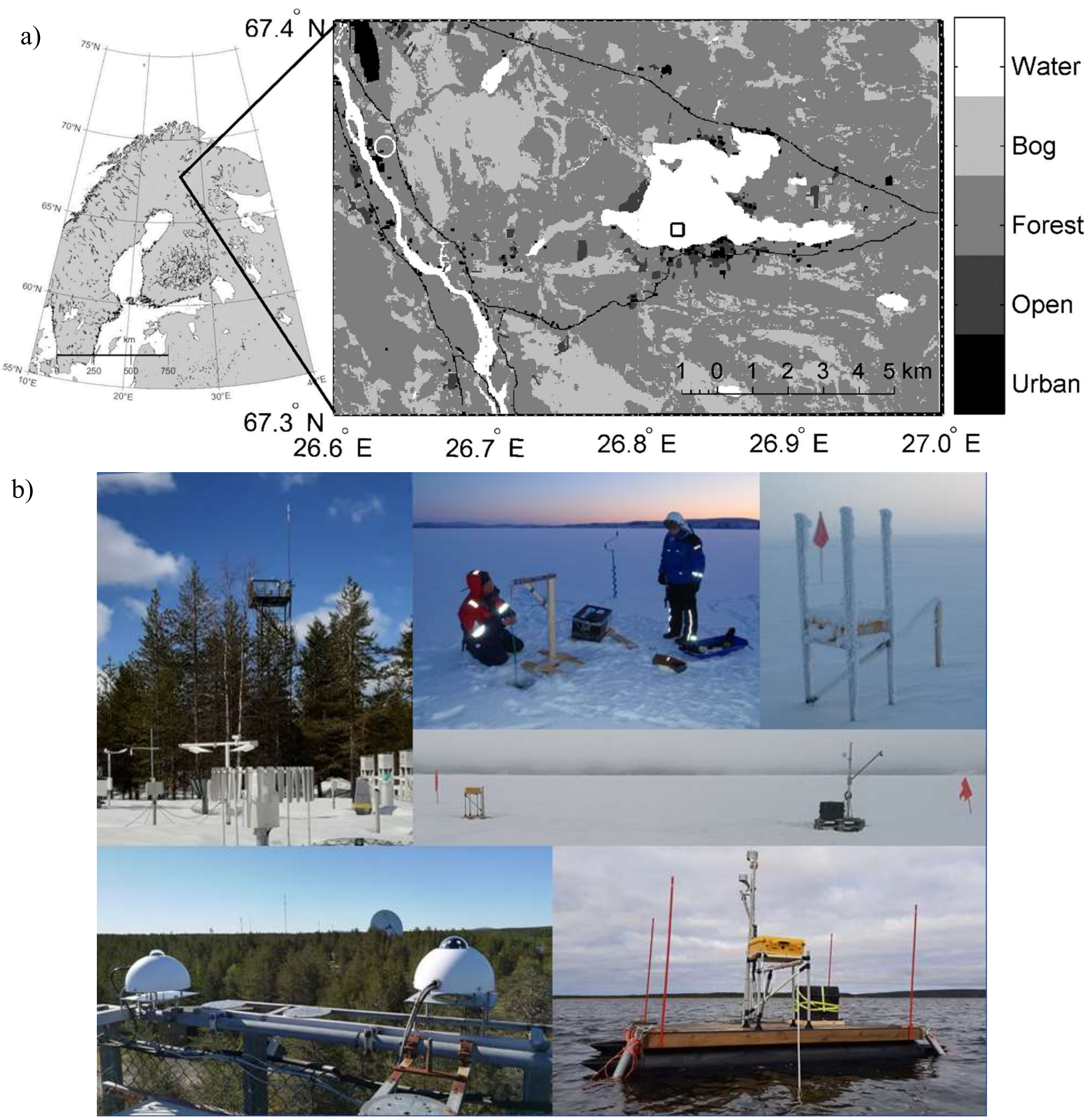


Figure 2. a) The location of Lak Orajärvi in Finnish Lapland and a map of lake Orajärvi and local catchment, where the open black square marks the SIMBA site and white circle is the Finnish Space

Centre. b) Snapshots of SIMBA deployment in Lake Orajärvi and a weather station at FMI-ARC main camp. A raft was anchored in the lake in October 2019 aiming to extend the lake observations beyond the ice season.

2.2 SIMBA

2.2.1 SIMBA program

SIMBA buoys have been deployed in Lake Orajärvi since 2009. The 2009 deployment was probably the internationally first SIMBA application for a lake study. In each winter when ice was formed in Lake Orajärvi, one SIMBA was deployed around mid-December at the same site, 67.35º N, 26.83º E, some 500 m from the shoreline. At the time of deployment, the snow depth, lake ice thickness and ice freeboard were measured. A supporting frame made of fiberglass was constructed on lake ice, and the SIMBA main control Peli case was placed on top of it (Fig. 2b). A separate wooden pole with scale was standing vertically to hold the thermistor string. An ice borehole was drilled through the ice layer, and the thermistor string was placed in it. The scene was left as it is, and then the thermistor string was frozen with surrounding water in the borehole. The SIMBA operated in the lake over the winter and most of the spring melting season. The recovery of SIMBA took place usually in late April but in some years as late as mid-May. Snow and ice conditions around the deployment site were documented and measured before dismantling the SIMBA camp. The documentation on SIMBA deployment and recovery is provided along with the SIMBA data as online files (see data availability). Table 1 summarizes the SIMBA deployment and recovery status.

Table 1. SIMBA deployment and recovery days and simultaneous manually observed snow depth (h_s), total ice thickness (H_i), and ice freeboard (H_{fb}, defined as negative if the lake water level was above the snow/ice interface) The seasonal mean values were derived from SIMBA-ET and SIMBA-HT observations. H_{gi} is the granular ice and H_{ci} is the congelation ice thickness.

Season	Deployment				Recovery					Seasonal mean ± STD				
	Date	h_s	H_i	H_{fb}	Date	h_s	H_{ci}	H_i	H_{fb}	H_i	h_s	H_{sfb}	H_{gi}	H_{ci}
	DD/MM/YY	(cm)			DD/MM/YY	(cm)								
2009/2010	16/12/09	5	27	0	07/04/10	31	54	64	5	NA				
2010/2011	SIMBA was not deployed; only manual observations every second week were available.													

2011/2012	19/12/2011	16	14	-4	12/04/2012	24	22	55	-3	38±16	22±6	5±2	15±10	23±7
2012/2013	12/12/2012	18	33	+1	25/04/2013	0	39	59	6	57±7	26±7	-5±3	4±4	53±4
2013/2014	12/12/2013	14	27	+1	30/04/2014	20	35	35	-3	49±7	17±4	-3±2	10±2	40±6
2014/2015	14/12/2014	19	30	-2.5	23/04/2015	2	35	69	4	54±11	24±7	-4±3	16±8	38±4
2015/2016	18/12/2015	18	27	-1	22/04/2016	5	30	71	6	60±16	19±7	-2±3	12±9	48±9
2016/2017	16/12/2016	8	31	-1	24/04/2017	10	38	72	4	58±13	19±6	-1±2	6±8	50±8
2017/2018	15/12/2017	25	23	-9	03/05/2018	0	28	55	6	48±15	24±6	-4±3	27±14	21±3
2018/2019	13/12/2018	15	19	-2	02/05/2019	1	20	55	6	51±17	21±7	-1±3	21±14	30±7
2019/2020	03/10/2019		-		12/05/2020	4	13	68	7	49±24	24±9	-1±3	32±20	20±5

The seasonal mean values of Hi, h_s, $H_{gi,}$ and H_{ci} were calculated by the SIMBA algorithm (Cheng et al., 2020). The seasonal mean value of ice freeboard (H_{sfb}) was calculated based on time series of snow depth *(h_s)*, granular ice thickness (H_{gi}) and columnar ice thickness (H_i) according to the Archimedes' principle: $H_{sfb} = H_i + H_{gi} - (h_s\rho_s + H_{gi}\rho_{gi} + H_i\rho_i)/\rho_w$, where ρ_s, ρ_{gi}, ρ_i and ρ_w are seasonal mean densities of snow, granular-ice and columnar ice and lake water, assumed to be 320 kg/m^3, 890 kg/m^3 and 910 kg/m^3 and 1000 kg/m^3, respectively. The STD is the standard deviation.

2.2.2 SIMBA buoy

SIMBA is a thermistor string-based Snow and Ice Mass Balance Apparatus. It has been developed by the Scottish Association for Marine Science (SAMS) Research Services Ltd (SRSL) in UK. SIMBA consists of a simple, robust thermistor string with 240 temperature sensors distributed evenly (2 cm intervals) along a 4.8 m long heat-shrink PVC plastic sleeve coated flat white wire. White heat-shrink sleeve is used to minimize the possibility of solar heating of the sensors. The accuracy of the SIMBA thermistor sensor is ± 0.1 ºC, which is comparable with other type of thermistor string based IMBs (Richter-Menge et al. 2006). Each sensor measures the environment temperature (SIMBA-ET). The resolution of the thermistor sensor is 0.0625°C, i.e., smaller changes cannot be detected even if the absolute accuracy of the sensor would allow it. In addition, the thermistor chain is equipped with heaters, i.e. resistor components mounted next to the temperature-sensing elements. A weak voltage (8 V) supply is connected to provide gentle identical heating of each sensor on the chain. The SIMBA heating cycle is usually long enough, often 60 or 90 s, for the temperature rise at the sensor to reach a steady state. Thermal conductivity determines how the heat is conducted away of the heated sensors placed in air, snow, ice and lake water. As a result, the SIMBA-HT profiles can greatly enhance the detection of the interfaces between air, snow, ice and water. The heating cycle is applied once per day. The SIMBA-HT is controlled not to disturb the SIMBA-ET measurements which are carried out typically 4 times per day (Jackson et al., 2013). A SIMBA also includes a built-in GPS to record SIMBA drift positions (for sea ice applications), a magnetometer for tilt and floe rotation, a barometer for surface air pressure, and an external sensor to measure near-surface ambient air temperature. An iridium modem is applied for data transmission. SIMBA has been used in various field campaigns targeting snow and ice mass balance in seasonally ice-covers in lakes (Cheng et al., 2014) and Polar Oceans (Hoppmann et al. 2015; Provost et al. 2017; Lei et al. 2018, 2021). Table 1 presents a summary of SIMBA observations in Lake Orajärvi.

2.3 Weather station

Meteorological data were collected at FMI-ARC station (67.3666°N, 26.6290°E, WMO code 02836) 11 km from Lake Orajärvi. The data sets include wind speed (*Va*), air temperature (*Ta*), relative humidity (*RH*), cloudiness (*cn*), longwave (*Ql*) and shortwave (*Qs*) radiation, snow depth on land (*Hs*) and precipitation (*Prec*) (Table 2). The radiative fluxes were measured on a 10-m high tower above treetops using Kipp&Zonen CM11 pyranometers (305-2800 nm) and Kipp&Zonen CG4 pyrgeometers (4500 - 42000 nm). Snow depth (Campbell Scientific SR50) and precipitation (OTT Pluvio2) at ground level were also measured. All measurements were taken once a minute and aggregated to 1-hour time intervals.

3 Data description

3.1 SIMBA data

The main output of a SIMBA buoy is the time series of environment (SIMBA-ET) and heating (SIMBA-HT) temperature measured at different depths from the lake water through ice and snow to air.

3.1.1 SIMBA-ET

For each season, we have up to 241 time series of temperature (SIMBA-ET) at different depths. For those sensors located in the air, the temperature differences between the sensors are small, as the air in the lowermost 1.5 m layer mixes effectively and the sensors are close to each other. The temperatures inside snow reveal much larger vertical gradients because snow has a small thermal conductivity. The temperature profile in ice has smaller vertical gradient compared to that in snow, since the thermal conductivity of ice is larger than that of snow. At the ice bottom, temperature is at the freezing point and gradually increases towards the lake bottom. Figure 3 shows an example of seasonal SIMBA-ET. One can estimate the heat fluxes within snow and ice, and those at the air-snow, snow-ice, and ice-water interfaces.

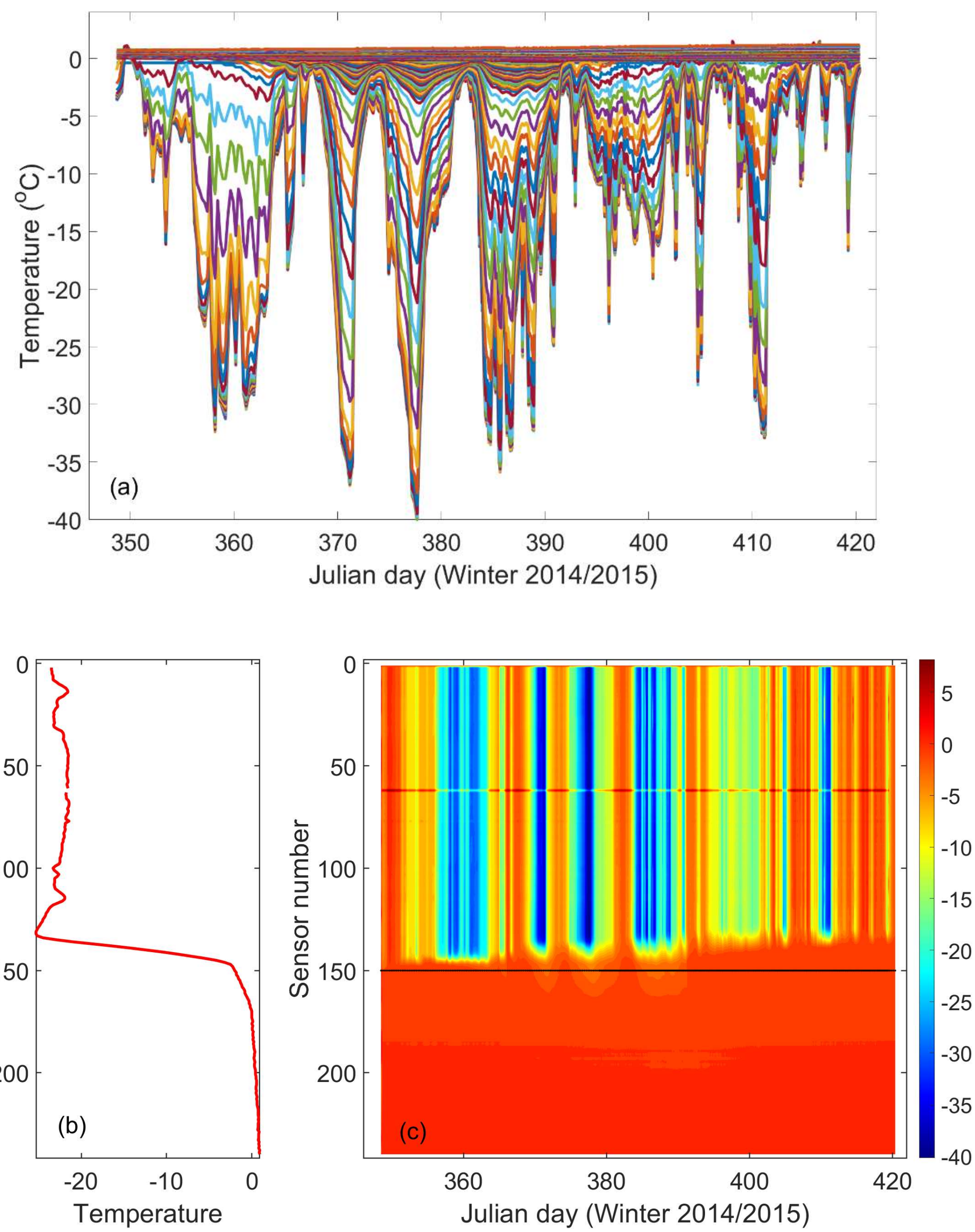
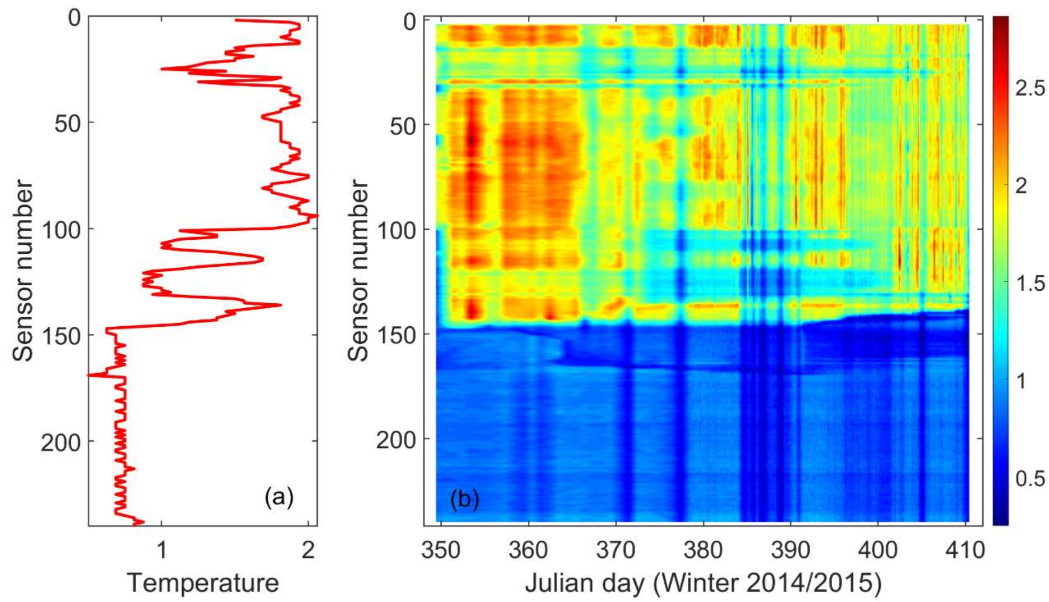


Figure 3. Illustrations of SIMBA-ET data: a) Time series of SIMBA-ET during observation period;

b) One snapshot (19 Jan 2014 08:00 UTC) of vertical SIMBA-ET profile through air-snow-lake ice-water; c) SIMBA-ET field observed by 240 sensors. Sensor 1 was placed in air and sensor 240 in water.

3.1.2 SIMBA-HT

SIMBA-HT shows the temperature increase in the medium each sensor was contacted during a short heating period of 60 s and 90 s. The temperature changes are largely dependent on the thermal diffusivity of the surrounding medium. Low heating power ensures that the temperature increasing will not be too high to melt snow and ice in contact with the sensor and guarantee a fast restore of environment temperature around the sensor before the next SIMBA-ET observation, and above all to minimize SIMBA power consumption. One example of SIMBA-HT is given in Figure 4.



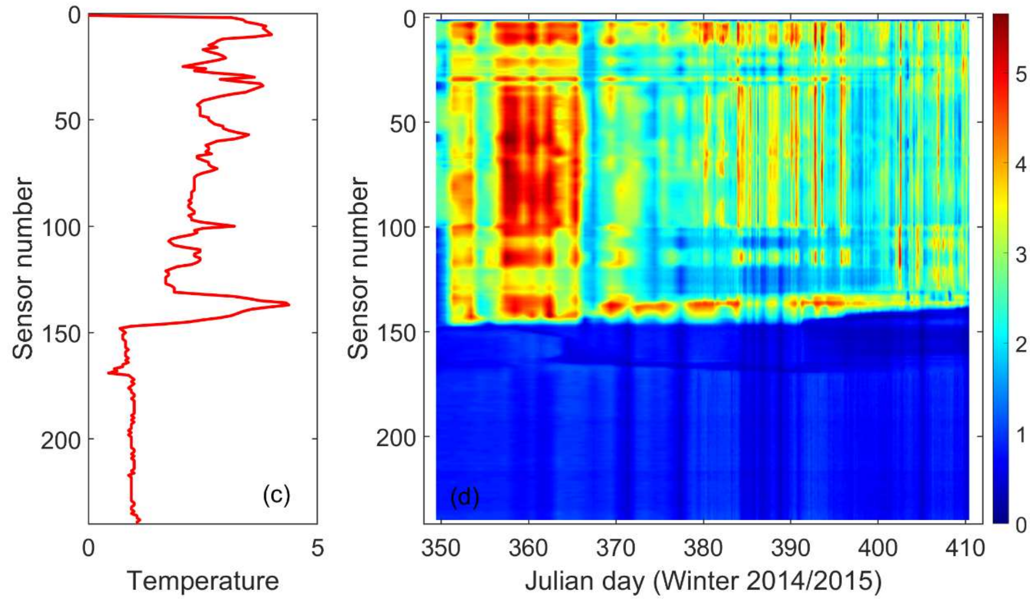


Figure 4. Illustrations of SIMBA-HT: a) a snapshot (25 January, 2015, 18:00 UTC) of vertical profile of observed temperature increase after 60 s., b) SIMBA-HT (60s) field observed by 240 sensors; c) Same as a) but after heating for 90 s., and d) SIMBA-HT (90s) field observed by 240 sensors;

3.1.3 SIMBA snow depth and ice thickness

Snow depth and ice thickness are derived from SIMBA-ET and SIMBA-HT data. A common procedure is to look SIMBA-ET temperature profiles manually and identify sudden changes of vertical temperature gradient to locate the air-snow, snow-ice and ice-water interfaces. The snow depth is then calculated as the distance between the air-snow and snow-ice interfaces, and the ice thickness is the distance between the snow-ice and ice-water interfaces. However, a manual procedure is a heavy task, especially if SIMBA operation covers long period or one would need real time SIMBA results. Several studies have been carried out aiming development of an algorithm to obtain snow depth and ice thickness automatically (Liao et al., 2019, Zuo, et al., 2019, Cheng et al., 2020).

Below we present an example of the application of the Cheng et al, (2020) algorithm to retrieve snow depth and ice thickness from SIMBA data observed in Lake Orajärvi. When SIMBA was deployed, the initial sensor position at snow-ice interface is known and we defined it as Z_{gi0}, i.e. zero reference position for granular ice. During observation period, in case if initial snow-ice interface is moving upward from Z_{gi0}, which is a common phenomenon in Arctic lakes, the distance between Z_{gi0} and moving snow-ice interface is the new granular ice thickness formed by snow to ice transformation.

The depth difference between total ice thickness and granular ice thickness is the congelation ice formed at the ice bottom. Figure 5 shows the air-snow, snow-ice and ice-water interfaces with SIMBA-ET (a) and SIMBA-HT (b) as the background. For better clarity, 5-day running average can be produced as the final products.

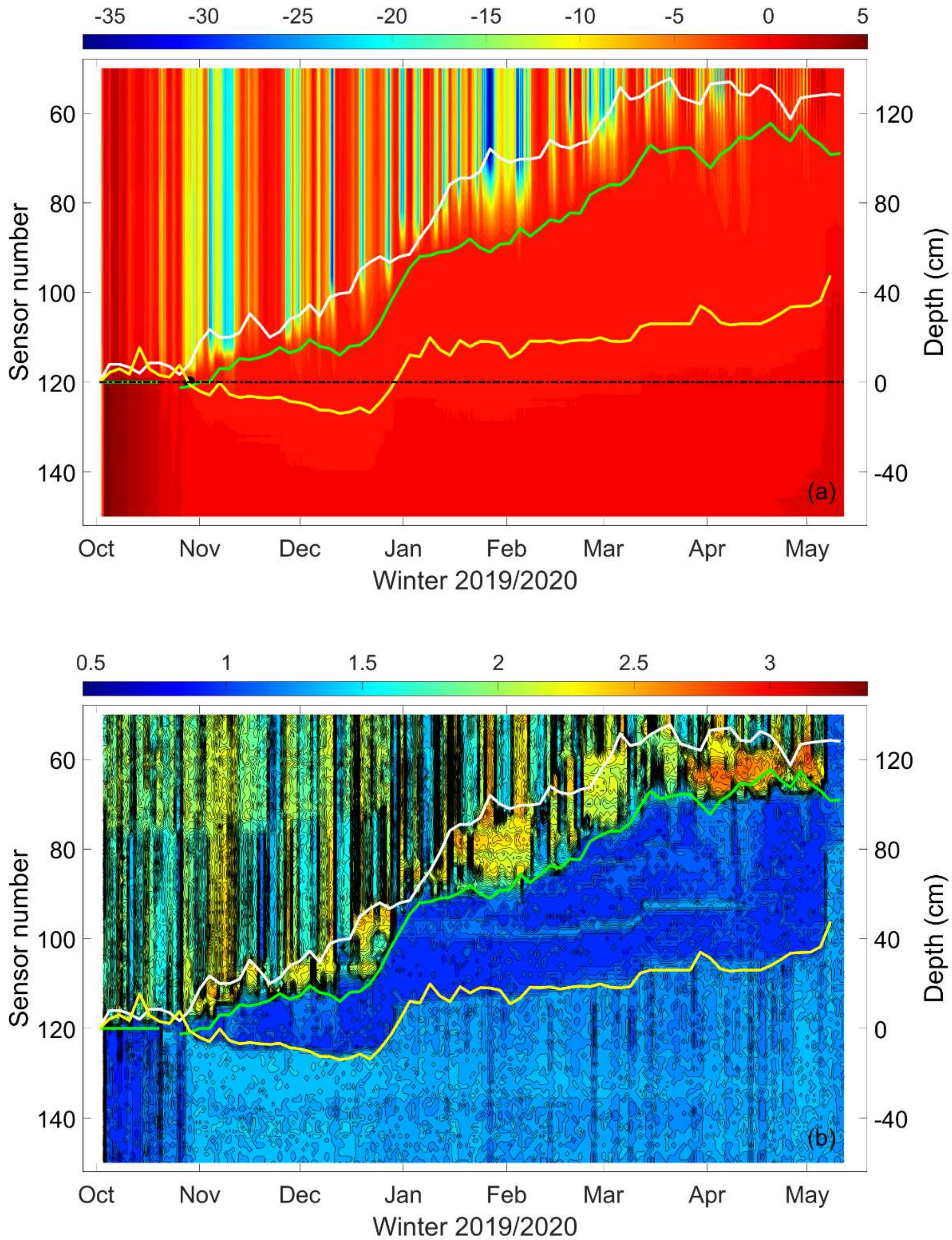


Figure 5. Time series of sensor position for the air-snow (white), snow-ice (green) and ice-water (yellow) interfaces, identified applying the SIMBA algorithm. The SIMBA-ET observation is

illustrated as background in a), and SIMBA-HT ratio (HT60/HT90) in b). The black dash line shows the sensor number (120) at the initial ice surface (Z_{gi0}). For clarity, we only illustrate sensors 50 – 150.

Using snow/ice interface as the zero-reference level, time series can be calculated for the snow depth, snow-ice thickness, total ice thicknesses, and ice freeboard. Figure 6 is an example of the 2019/2020 time series, indicating that the lake ice was mainly granular ice, which was related to heavy snow fall during the ice season (the snow depth observed at FMI-ARC weather station on land was highest in a decade).

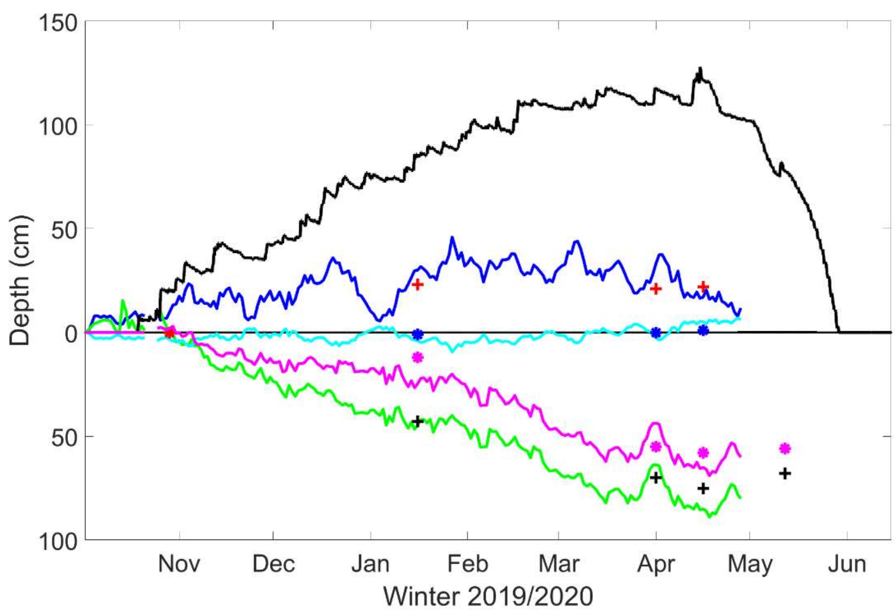


Figure 6. Products derived on the basis of SIMBA data: snow depth (blue), ice freeboard (cyan), granular ice thickness (magenta), and total ice thickness (green). The symbols represent manual observations of snow depth (+), ice freeboard (●), granular ice thickness (●) and total ice thickness (+). The black solid line denotes the snow depth on land.

3.2 Weather data

The observed daily mean values of meteorological parameters for all seasons are presented in Figure 7. The inter-annual mean, maximum and minimum air temperatures are -2.5 ºC, -16.5 ºC and -5.5 ºC, respectively. The air temperature reveals a constant decreasing pattern from November to January. The coldest months are January and February. From March onward, the air temperature increased gradually due to increasing solar radiation (Fig. 7c). The inter-annual average, maximum and minimum downward longwave radiative fluxes are 259 W/m^2, 309 W/m^2, and 201 W/m^2, respectively. The corresponding values for downward shortwave radiative fluxes are 64 W/m^2, 97 W/m^2, 26 W/m^2.

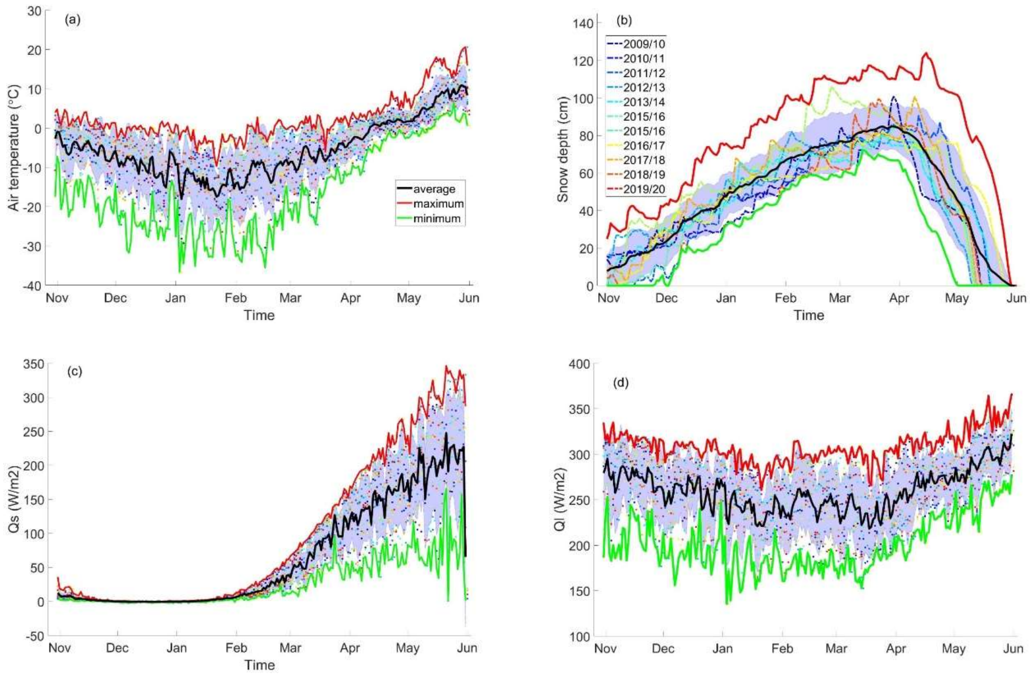


Figure 7. The observed (dots) daily mean air temperature (a), snow depth (b), downward shortwave (c), and longwave (d) radiative fluxes for each ice season between 1 November and 31 May. The solid lines represent decadal daily maximum (red), minimum(green) and average (black) values. The shadow area represents the standard deviation (STD). For snow depth, daily mean values are given as thin color lines.

Table 2 Summary of various meteorological and physical observations between 1 November and 31 May. For meteorological parameters (*Va*, *Ta, RH, cn, Qs, Ql*) the values are seasonal mean ± standard deviation.

Season	*Va* *m/s*	*Ta* *ºC*	*RH* *(%)*	*cn* *(-)*	*Qs* *W/m^2*	*Ql* *W/m^2*	*Tprec* *(mm)*	*Hsmax* *(cm)*	*AFDD* *ºC*	*ATDD* *ºC*
2009/2010	2.2±0.3	-6.8±9.4	84±9	0.7±0.1	62.9±76.8	267±31	201	101	-1717	304
2010/2011	2.2±0.6	-8±9.5	83±9	0.6±0.1	64.1±76.5	259±27	157	72	-1955	286
2011/2012	2.4±0.4	-5.1±7.2	84±11	0.7±0.1	64.4±82.3	264±21	272	91	-1308	239
2012/2013	2.2±0.2	-6.3±8.5	80±13	0.6±0.2	67±85.6	250±31	192	82	-1683	346

2013/2014	2.6±0.4	-4.6±6.4	81±10	0.7±0.1	61.6±81.8	261±19	267	81	-1214	243
2014/2015	2.7±0.6	-4.3±6.6	84±8	0.7±0.1	55.8±67.2	264±21	286	87	-1148	249
2015/2016	2.3±0.3	-4.2±8.4	84±10	0.7±0.1	61.5±81	265±25	287	106	-1261	354
2016/2017	2.8±0.3	-5.9±4.7	81±10	0.7±0.1	64.9±81.2	252±14	186	82	-1338	101
2017/2018	2.5±0.4	-6±8.7	80±12	0.7±0.2	66.5±82.7	256±27	219	101	-1615	362
2018/2019	2.7±0.4	-5.4±7.9	84±10	0.6±0.1	63.5±79.8	258±26	256	100	-1432	293
2019/2020	2.8±0.5	-5±5.1	84±13	0.6±0.1	70.1±92.9	258±13	285	124	-1242	188

Tprec: total accumulated precipitation in water equivalent (mm); Hsmax: the maximum observed snow depth on land.
AFDD: The accumulated freezing degree day: the sum of daily mean air temperature below freezing point; ATDD: The accumulated thawing degree day: the sum of daily mean air temperature above freezing point.

Figure 7b clearly indicates that snow depth for the 2019/2020 season represented an extreme condition in a decade. There is an increasing trend of total precipitation during the ice season (Fig. 8). The total seasonal accumulated total precipitation is highly correlated (correlation coefficient r = 0.93) with the seasonal mean air temperature. The correlations between seasonal mean/maximum snow depth and corresponding air temperature are much lower r = 0.40 and r = 0.38, respectively. The correlation between total accumulated precipitation and maximum snow depth was 0.55. The difference is contributed by the snow drift and changes of snow metamorphism.

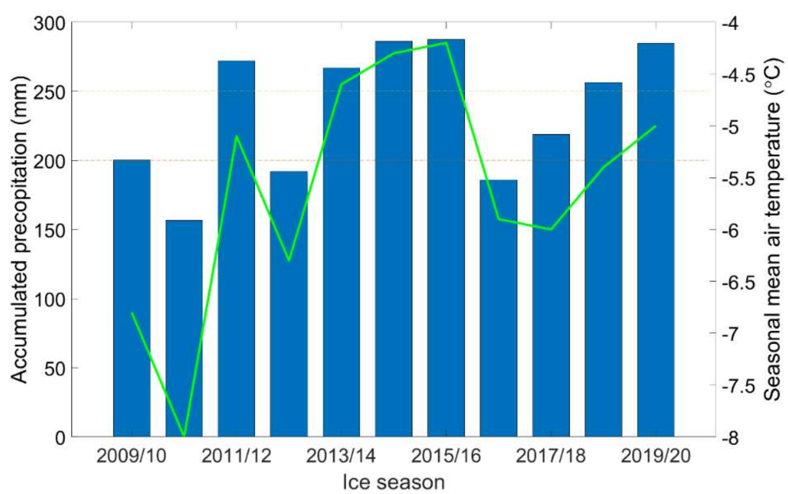


Figure 8. The accumulated total precipitation and mean air temperature between 1 November and 31 May.

4. Discussions

4.1 Inter-annual variation of SIMBA snow and ice products

Applying the SIMBA algorithm (Cheng et al., 2020), we obtained lake snow and ice products for all seasons (see data availability). Figure 9 shows the observed seasonal maximum values for the snow depth, maximum total ice thickness, and maximum granular ice thickness. During the observation period, both snow depth and ice thickness showed increasing trends. The increase of granular ice thickness is the fastest among all the snow and ice components. It reached the maximum 80% of the total ice thickness in 2019/2020. In Lake Orajärvi, snow mass has contributed to the ice thickness during every winter season. The maximum granular ice thickness was on average about 40% of the maximum total ice thickness during the data period. For all seasons, the correlation coefficient between the maximum granular ice thickness and the maximum ice thickness was 0.64. The occurrence of maximum lake snow is, on the average, about one month prior to the maximum granular ice formation (Fig. 10). Because of snow to ice transformation, the time series of snow depth in the lake is not correlated with the snow depth on land. The snow depth on lake ice ranged from 25 to 43% of that on land. On the average the ratio was 0.33, some 11% less than observed for a lake in southern Finland (Kärkäs, 2000). In several seasons, when SIMBA were recovered in late April or early May, the entire snow layer on lake ice was transferred to granular ice. Granular ice reached its maximum value when the ice surface was free of snow.

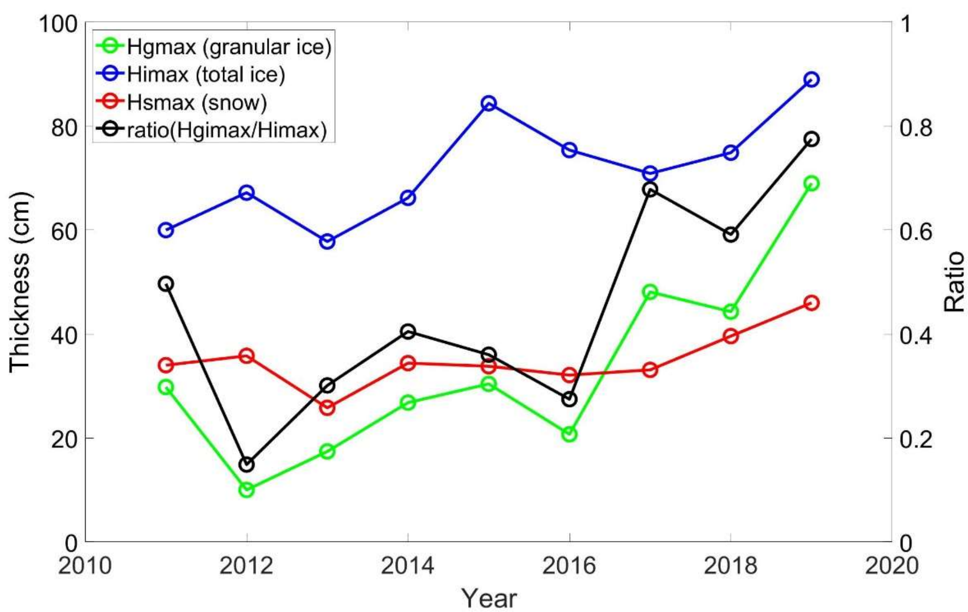


Figure 9. SIMBA observed seasonal maximum snow depth (red), maximum total ice thickness (blue), maximum granular ice thickness (green) and the ratio between granular ice and total ice thickness (black) during observation seasons.

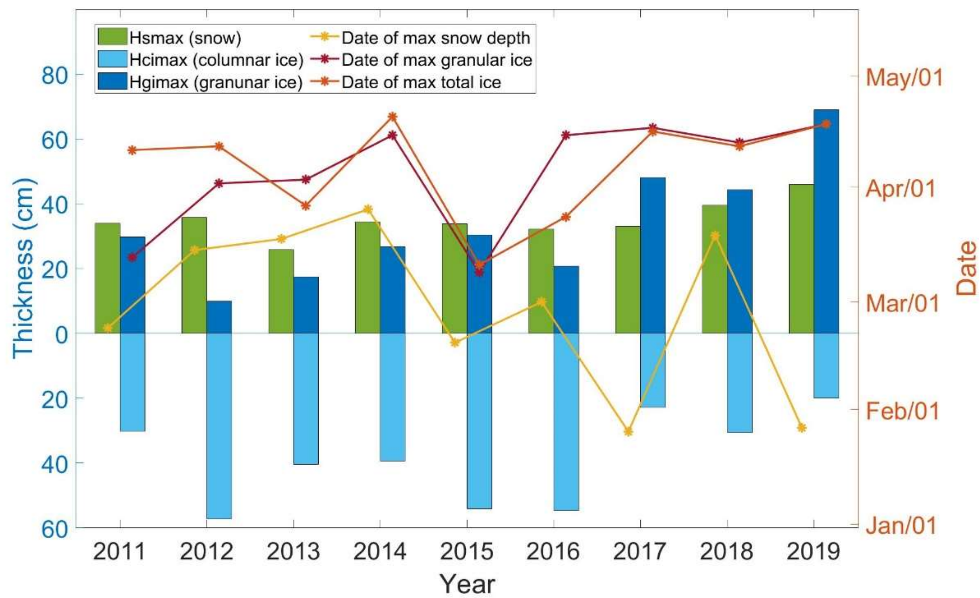


Figure 10. Seasonal maximum snow depth, granular ice thicknesses, congelation ice thicknesses, and the date when those values were observed.

4.2 Inter-annual variation of temperature conditions

According to weather observations in Sodankylä, the air temperature increased by about 0.16 ºC/year during the last deacde. For the period from 1980 – 2020, the air temperature has an increasing trend of about 0.06 ºC/year. On the average, the increase of air temperature in last decade is about 3 times faster than the past 40 years in agreement with the findings of Przybylak and Wyszyński (2020) for the high Arctic. The accumulated precipitation correlated better to the maximum snow depth on land (r = 0.55) than the mean snow depth (r = 0.45). It is, however, not correlated (r = 0.21) with snow depth on the lake ice.

The seasonal AFDD and ATDD for each winter season are shown in Figure 11. A negative decreasing of AFDD was seen in response to the increase of air temperature. AFDD is directly linked with thermodynamic ice formation. During a given period, a decrease of AFDD is expected to result in less formation of columnar ice. However, during our observation period, the total ice thickness revealed an increasing trend. The increase of ice thickness is due to snow-ice formation. The trend of

ATDD is very insignificant, suggesting that the melting of lake ice due to temperature increase has not increased much during the observation decade.

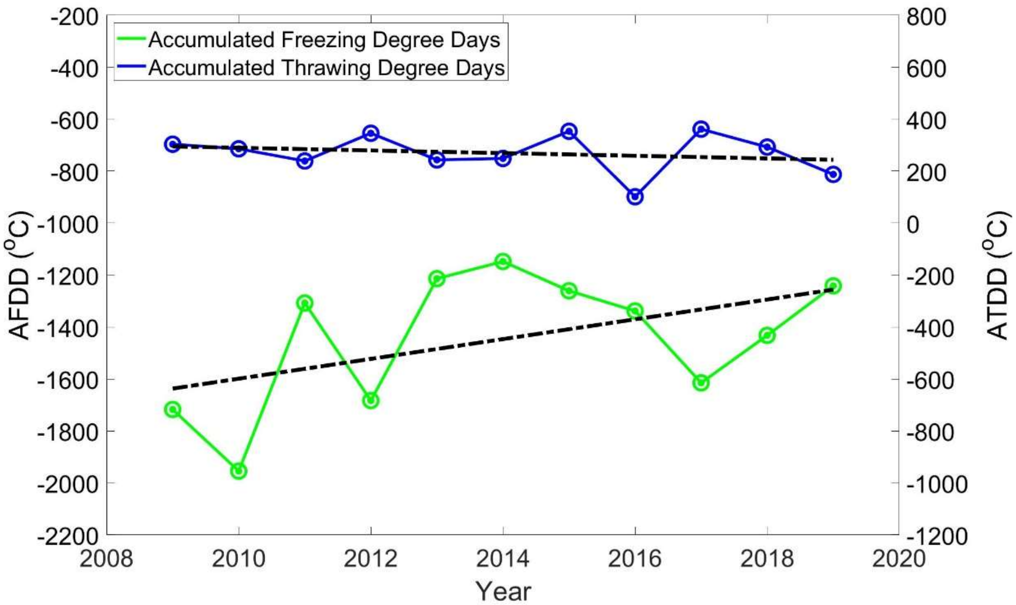


Figure 11. The seasonal accumulated freezing degree day (AFDD) and thaw degree day (ATDD) during the observation period (2009/2010 – 2019/2020).

4.3 Challenges of the SIMBA program

SIMBA observations in Lake Orajärvi represent a small but sustainable program, so far ran for a decade. A few times we have encountered malfunction of SIMBA, especially in the early phases of the SIMBA program. In recent years, SIMBA has become more robust without need for heavy-duty maintenances during field measurements, and the system has been remarkably improved with respect to the quality of HT measurements. Several snow and ice products can be derived from SIMBA's two type of temperature (SIMBA-ET and SIMBA-HT) measurements. The SIMBA program has largely benefited from the Sodankylä supersite infrastructure, where the comprehensive and high standard meteorological observations are available.

Challenges remain in further improvement of the SIMBA program. Due to safety issues, SIMBA must be deployed and recovered when ice is strong enough. Hence, the early freeze-up and late break-up cannot be monitored. In Autumn 2019, a wooden floating raft was deployed and anchored in Lake Orajärvi. SIMBA was, for the first time, deployed during ice-free season on 1 October. This kind of deployment will be carried out also in the future, allowing year-round SIMBA measurements.

Part of the thermistor chain exposed in the air above the snow surface may suffer from frost in winter or from solar heating in spring, and also the sensors in the upper layers of snow and ice may suffer from solar heating, resulting in large uncertainties in SIMBA-ET and SIMBA-HT readings. To compensate the effect of temperature errors on snow depth detection, one solution is to deploy Acoustic Rangefinder Sounders (ARS) to measure the evolution of snow surface. In fact, an ARS has been deployed in the past two winter seasons. These data sets can also be used to understand the effect of wind on snow drift and quantify snow surface sublimation in winter.

During the melting season, both SIMBA-ET and SIMBA-HT strongly raise in the upper part of the ice resulting an isothermal status of the entire ice column. In this condition, SIMBA snow depth and ice thickness values are liable to large errors. Combination of SIMBA observations and numerical model experiments may yield more reliable results in such conditions.

SIMBA measurements have been taken automatically, but it is still important to carry out manual on site observations, such as collecting ice core and snow samples, as such observations cannot be made by automatic instruments.

4 Data availability

The data are archived at https://zenodo.org/record/4559368#.YEIYOtyxVPZ (Cheng et al., 2021). The 4 zip-files should be unzipped in different file folders preferably using zip-file names as the folder names. A readme file exists in each folder. The manual in situ snow depth and ice thickness observation for 2009/2010 - 2012/2013 as well as a description of SIMBA deployment and recovery for each ice season (SIMBA_D&R_all_Years.docx) are provided.

5 Conclusions

A thermistor string-based snow and ice mass balance apparatus (SIMBA) has been deployed in an Arctic lake since 2009. The measurements covered most part of the ice season from mid-December to late April/early May. SIMBA-ET and SIMBA-HT temperature observations are described in this paper. The daily snow depth and ice thickness were derived from SIMBA temperature field applying a validated automatic algorithm (Cheng et al., 2020). The meteorological parameters for winter seasons (1 November - 31 May) are also collected and discussed. During the investigation decade, the air temperature in the ice season has had an increasing trend of 0.16 ºC/year. The warming rate is comparable to the result find for the high Arctic by Przybylak and Wyszyński (2020). The increase of air temperature in winter season is highly correlated (0.93) with seasonal total accumulated precipitation. This is because warm winters in the study region are also wet and characterized by a high cyclone activity. Transient cyclones are vital for the transport of warm, moist air masses to Northern Europe (Wickström et al., 2020). The precipitation in season 2019/2020 represented an extreme episode during the study decade. Despite of the air temperature increase, the total maximum ice thickness in the lake has an increasing trend. The increase of maximum ice thickness is due to the increase of granular ice. The interannual variability of maximum granular ice thickness is large ranging from 15 to 80% of the total maximum ice thickness. The time series of the SIMBA ET and HT allow identification of moving air-snow, snow-ice and ice-water interfaces. Because of the air temperature increase, the seasonal AFDD reduces. This results in a decreasing impact of below-zero air temperatures on lake ice growth during the freezing season, as the growth of columnar ice is reduced. Simultaneously, the role of precipitation on total ice formation is enhanced because snow-ice and superimposed ice contribute to an increasing fraction of the total ice thickness. The trend in ATDD was negligible, suggesting that the effect of air temperature on ice melting has remained unchanged.

To our knowledge, this is the first decadal-scale SIMBA data set ever collected from an Arctic lake. The data provides information on snow and ice mass balance and the controlling atmospheric factors. The measurements will continue in the future.

The weather observations, e.g. decadal time series of daily maximum and minimum weather parameters, can be used to estimate snow and ice conditions in the lake applying a snow/ice model (e.g. Cheng et al., 2014). The SIMBA data are not only suitable for snow/ice surface heat and mass balance studies. The temperatures at the ice bottom and in the water below are valuable to understand the lake thermal structure and water-ice heat transfer (Huang et al., 2019b).

The SIMBA program, with Lake Orajärvi as a testbed, offers excellent opportunities for dissemination of cryospheric knowledge and related outreach, providing rich possibilities for community collaborations both nationally and internationally. The observed changes in snow depth and composition of lake ice contribute to better understanding of cryospheric aspects of climate change. For example, parameterizations of the discovered snow and ice processes can be improved in climate models.

Snow and ice measurements similar to those in Lake Orajärvi have been recently initiated in Wulaingsuhai lake in an arid climate zone in Inner-Mongolia of China. The observations focused on lake ice mass balance (Lu et al., 2020) and energy budget, in particular the solar radiation (Cao et al., 2020). In a long run, the corresponding lake snow and ice measurements at both sites and possible similar observations in a thermokarst lake (e.g. Huang et al, 2019a, 2019b) at Qinghai-Tibet Plateau, often referred to as the “Third Pole of the Earth” can be used together to carry out coordinated research.

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