22nd IAHR International Symposium on Ice
Singapore, August 11 to 15, 2014

The Impact of Air Temperature and Precipitation on Formation of Lake Ice in Northern Finland

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The formation of lake ice strongly depends on the heat exchange at the ice-water interface, the radiative and turbulent heat fluxes at the ice/snow surface, as well as on precipitation. In Northern Finland, snowfall is guaranteed for each winter season, so the lake ice is composed by columnar ice (ice formed via bottom growth) and granular ice (snow-ice, superimposed ice). The impact of air temperature and precipitation on lake ice formation is investigated. The meteorological measurements from Sodanlylä weather station, northern Finland was used as external forcing to run a snow and ice model (HIGHTSI) for a climatological period 1980/1981 – 2012/2013 (33 winter seasons).

The inter-annual variations of meteorological measurements are large. The air temperature increasing trends ($P < 0.05$) for annual cycle (AC: 1 July – 30 June) and freezing season (FS: 1 Nov. – 30 April) are 0.68°C/10yr and 0.78°C/10yr, respectively. The biggest temperature increasing trend was 2.1°C/10yr in December. The total precipitation in FS slightly increased ($P > 0.05$). The increasing of liquid precipitation ($P < 0.05$) in FS results from temperature warm up. The validations of modelled snow and ice parameters in lake Orajärvi (freeze up date, thickness, snow onset melting and breakup date) was limited to the available *in situ* data sets, but in general the results were in line with available observations and showed reasonable variations in response to the weather forcing. The ice thickness showed a decreasing trend ($P < 0.05$). The portion of modelled ice composition (columnar and granular ice) showed periodically variations in 80s (columnar dominate), 90s (equally important of columnar and granular ice) and new millennium (decreasing of columnar and increasing of granular ice). For few extreme mild winters, the modelled lake ice thickness was thin, which was coherent with the overall sea ice condition in the Baltic Sea indicating that the weather forcing is a primary driving force for the ice formation.

Proceedings of the 22nd IAHR International Symposium on Ice

ISBN: 978-981-09-0750-1
doi:10.3850/978-981-09-0750-1_1263

1 Introduction

In freshwater lakes the water column is well mixed before freezing. When ice is formed the water temperature structure under the ice is usually quite stable making the meteorological condition a primary driving force for thermodynamic growth of lake ice. So the inter-annual variation of lake snow and ice status, particularly in far north, can be used as a proxy to explain the changing climate because climate warming in high latitude region is faster than any other place on earth (Blunden and Arndt, 2012). Lake ice is a sensitive indicator of climate change. The ice season becomes shorter in many high-latitude boreal lakes (Jensen et al. 2007). Investigation of long term snow and ice parameters in lake and their changes linked with synoptic-scale atmospheric forcing is a common method on lake ice phenology research (e.g. Lei et al., 2012). The lake ice model simulations can understand better the sensitivity of climatological change, for example, the increase of air temperature to the change of ice season length and thickness variations (Yang et al, 2012).

In this paper, the trends of climatological weather forcing factors measured in Sodankylä weather station (1980-2013), northern Finland are investigated. The inter-annual variation of freeze up, snow and ice thickness, onset of snow melting, final break up as well as composition of ice column were simulated by a thermodynamic snow/ice model (HIGHTSI).

We want to identify the order of importance of various forcing factors controlling inter-annual variability in lake snow and ice. We investigate the trends of modelled snow and ice parameters to better understand how lake snow and ice in response to inter-annual variation of weather forcing. The correlation coefficient and significance testing among various modelled snow and ice parameters are also carried out.

2 Thermodynamic snow and ice model

A high-resolution thermodynamic snow and ice model (HIGHTSI) was used to calculate the evolution of snow and ice thicknesses (Launiainen and Cheng, 1998, Cheng et al., 2003, 2006, 2008). The model has been further developed and adapted to investigate lake snow and ice (Semmler et al., 2012, Yang et al., 2012; 2003). The thermodynamic energy and mass balance and interactions between air-snow, snow-ice and ice-water in vertical direction are solved in HIGHTSI. The surface heat balance equation is used to solve the surface temperature and melting. In this study, shortwave and longwave radiative fluxes are parameterized (Zillman 1972, Key et al. 1996). The global radiation penetrating through the surface layer is parameterized, making the model capable of calculating sub-surface melting quantitatively. The turbulent surface fluxes are parameterized taking the thermal stratification of the atmospheric surface layer into account. A sophisticated albedo scheme which has been applied for climate and process models is used in this study (Briegleb et al. 2004). At the snow-ice interface, the snow-to-ice transformation processes through re-freezing of flooded lake water or melted snow are considered in the model (Saloranta, 2000, Cheng et al., 2003, 2006). In the HIGHTSI model, we calculate thickness of snow, slush, snow/ice, superimposed ice, columnar ice. The snow thickness is affected by precipitation, snow melting and flooding slush formation. The density of snow is parameterized according to Anderson (1976). The slush is formed by lake water flooding slush and snow melting. The flooding slush is a result of isostatic imbalance of overload snow on top of total ice floe. The melting slush is created by surface and sub-surface snow melting and this part of slush is allowed to be re-frozen to create superimposed ice before the onset of ice melt. The density of slush is calculated as a function of density of snow, ice and water (Saloranta, 2000). Snow-ice is formed by refreezing of flooding slush. The superimposed ice is formed via refreezing of snow melting. For fresh lake water, we assume that the densities of snow-ice and superimposed ice are the same. For the sake of simplicity, snow-ice and superimposed ice are assumed to form at snow-ice interface (Saloranta, 2000; Cheng et al., 2003; Semmler et al., 2012, Cheng et al., 2014). At the lower boundary, the ice growth/melt is calculated on the basis of the difference between the ice-water heat flux and the conductive heat flux in the ice. If the conductive heat flux at the ice bottom is larger (smaller) than the heat flux from the lake, the ice grows (melts) from the bottom. In this study, the heat flux from the lake was prescribed to a small value of 1.5 W/m^2 for the freezing season, increasing to 5 W/m^2 after the onset of ice melt, because penetrating solar radiation heats the lake water below ice.

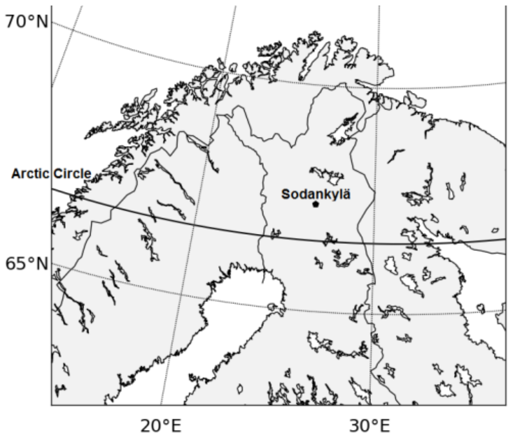

Figure 1. The research site Sodankylä is located in northern Finland within the Arctic cycle.

3 Data

The research site was located in the vicinity of the Arctic Research Center of FMI in Sodankylä, northern Finland (67.368 N, 26.633 E, Fig.1). The station is surrounded by sparse pine forest where most of the trees are less than 12 meters high. The area is characterized by mires and sparse pine forests with low undergrowth of grass, lichen, mosses and sprigs. The study site usually experiences permanent snow cover from early October to mid-May.

The subarctic climate and the geographic location in the north-western part of the Eurasian continent, under the influence of Atlantic Ocean, Arctic Oceans as well as the Baltic Sea, enable high annual and monthly variation in weather conditions, making possible the development of very different kinds of snowpack structures in land (Tikkanen, 2005) and snow/ice composition in lakes (Cheng et al, 2014). Temperatures below - 35 °C are typically experienced in January and February but near-zero temperatures are possible throughout the whole winter. Cloud cover presents frequent in winter. The weather station data from beginning of 1980 to the end of 2013 is used in this study. The wind speed (V_a) air temperature (T_a) and relative humidity (*Rh)* were measured every 3 hours before 2008. Since 2008 measurements have been made every 10 minutes. The total precipitation (*PrecT*), cloudiness (*Cn*), and snow depth in land (HS_L) were measured manually before a major upgrade of measurement equipment in early 2008. Since then, snow depth and cloudiness have been measured automatically. All the weather parameters used in this study were linearly interpolated to 1h time step. The separation of solid and liquid precipitation largely replies on the temperature (Auer, 1974). This temperature value is highly geographically dependent, varying from -1.0 ºC up to 2.5 ºC in northern Eurasia (Ye et al., 2013). We applied 0.5 °C to separate solid (*PrecS*) and liquid (*PrecL*) values (Yang et al, 2012).

4 Results

For convenience, the annual cycle (AC) is defined from 1 July to the 30 June. The ice freezing season (FS) is between 1 November and 30 April, and the rest part of year (1 May - 31 October) refers to the warm season (WS).

4.1 Long term variations of weather forcing factors

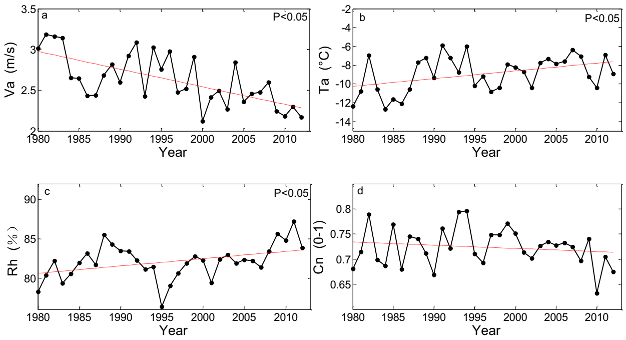

Figure 2. The inter-annual variations of FS mean (black lines) weather forcing factors of a) wind speed; b) air temperature; c) Relative humidity and d) Cloudiness. The red broken lines are the trends.

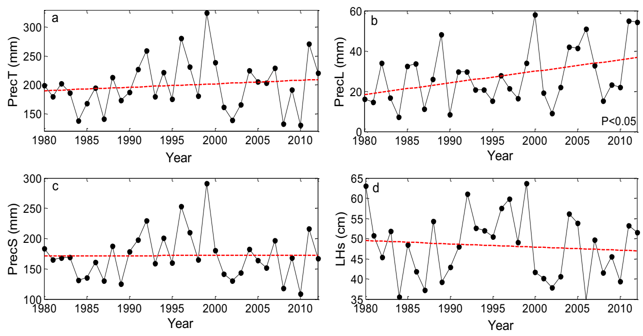

Figure 3. The FS accumulation (dot-connected line) of a) total precipitation; b) liquid precipitation; c); solid precipitation and d) average seasonal snow thickness in land.

During FS season, weather forcing showed large inter-annual variations. The wind speed has a decreasing trend ($P < 0.05$, Fig. 2a) while the air temperature ($P < 0.05$, Fig. 2b) steady increased with a magnitude of about 0.78 ºC/10yr. The temperature trends for AC and WS means are 0.68 ºC/10yr and 0.51 ºC/10yr, respectively indicating a more pronounced warm in FS season. The detail monthly mean statistical analyses suggested that the biggest temperature increasing trend was in December (2.1 ºC/10yr). The air moisture showed an increasing trend ($P < 0.05$, Fig. 2c), while the cloudiness has a decreasing trend ($P > 0.05$, Fig.2d), i.e. less cloud in winter, particularly in recent years. The total precipitation in FS slightly increased of about 6mm/10yr, roughly but without reaching a significant level ($P > 0.05$, Fig. 3a). Increasing of liquid precipitation (Fig. 3b) is associated with increasing of temperature ($P < 0.05$). The solid precipitation has no significant trend. The seasonal mean snow thickness in land showed large inter-annual variations consistent with the total accumulated precipitation in FS season. The snow thickness in land showed a decreasing trend ($P > 0.05$) roughly 8mm/10yr. The decreasing of seasonal mean snow thickness is linked with the increasing of air temperature.

The analyses of synoptic weather system in the study region revealed that in winter season, the weather pattern tends to be dominated by the interaction between low pressure from Atlantic Ocean and south edge of high pressure from Arctic region. When the low pressure prevails, the westerly wind carries warm-wet-air from north Atlantic sea leading to an increasing of air temperature in the Sodankylä region. If the synoptic weather pattern was controlled by the high pressure from eastern high Arctic, the local weather may reveal weak easterly wind accomplished with cold and dry air. The synoptic weather analyses revealed a very good positive correlation between FS temperature in each winter month and the North Atlantic Oscillation (NAO) index. Overall the significant level reaches 0.05, in which some of them were 0.01 level.

If the NAO index is positive (negative), the westerly wind anomalies will strong (weak), prevailing of warm and moisture (cold and dry) air and consequently reveal warm (low) temperature in the region.

Table1. The correlation coefficients between T_a and year (during 1980 –2013) and between various observed meteorological parameters in each winter month and FS season.

	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	FS
T_a	0.35	0.39	0.33	-0.10	-0.05	0.33	0.35
$PrecT/T_a$	0.55	0.48	0.28	0.16	0.19	-0.08	0.38
$PrecS/T_a$	0.20	0.36	0.26	0.11	0.12	-0.27	0.24
$PrecL/T_a$	0.72	0.59	0.26	0.41	0.41	0.32	0.40
NAO/T_a	0.44	0.33	0.44	0.56	0.78	0.32	0.44
number in red: $P < 0.05$; number in blue $P < 0.01$							

4.2 Long term variation of modelled snow and ice thickness

Each model run was carried out from 1 July until 30 June. The initial snow and ice thickness were set to be 0.01m and 0.02m, respectively. In July the weather condition is not favorable to any ice formation, so the snow and ice thickness will remain as the initial values. The snow and ice will start to grow when weather conditions favor a freezing condition. This is a crude approximation to determine the freeze up date (Yang et al., 2012). In practice the date of freeze up (accordingly break up) has three terminologies referring different stages of lake freezing and melting (Palecki, M. A. and Barry, R. G. 1986). As a first order estimation, the modelled freeze up date was when ice reaches 0.05m and corresponding snow was 0.02m, respectively. We may argue such a freeze up date refers to the earliest possible date of ice formation near the shore. The breakup date was when calculated ice thickness becomes zero.

The modelled snow and ice thickness for the 33 seasons are given in Figure 4a. The modelled initial freeze up date was 300 (27, October) ± 12 days; the onset of snow melting was 460 (5, April) ± 10 days; snow-free date was 483 (28, April) ± 7 days and the final break-up date was 518 (3, June) ± 8 days. The observed first snow accumulation (Hs > 0.02m) date in land was 301 (28, Oct) ± 13 days; the onset of land-snow melting was 460 ± 11 days same as lake onset snow melting date. The land snow-free date was 499 (14, May) ± 8 days. The correlation coefficient between land snow accumulation date and calculated lake freeze up date was 0.81. The correlation coefficient between land snow and lake ice free dates was 0.75. The spring onset snow melting in land and lake occurred at the same time and the correlation coefficient was as high as 0.89. This suggest that the surface heat balance is a dominate factor to affect the surface melting for both land and lake snow. Unfortunately, we do not have entire 33 seasons freeze up and breakup dates observation in Orajärvi lake. The measurements by Finnish Environmental Institute (SYKE) from other lake nearby suggested a reasonable match of freeze up date compared to our calculation. The SYKE observed breakup dates are 5-10 days earlier than our calculation because wind can break up ice floes and this process was not considered in our modelling.

The inter-annual variation of modelled average and maximum snow and ice thicknesses are given in Figure 4b. The seasonal average snow thickness was 0.15 m ± 0.02 m. The maximum snow thickness has large inter-annual variation ranging from 0.18 m - 0.34 m with average of 0.25m. No significant trend was detected. The seasonal average ice thickness was 0.42m ± 0.06

m. The modelled maximum ice thickness ranges from 0.46 m to 0.81 m with a mean value of 0.66 m. The modeled ice thickness showed a decreasing trend ($P< 0.05$).

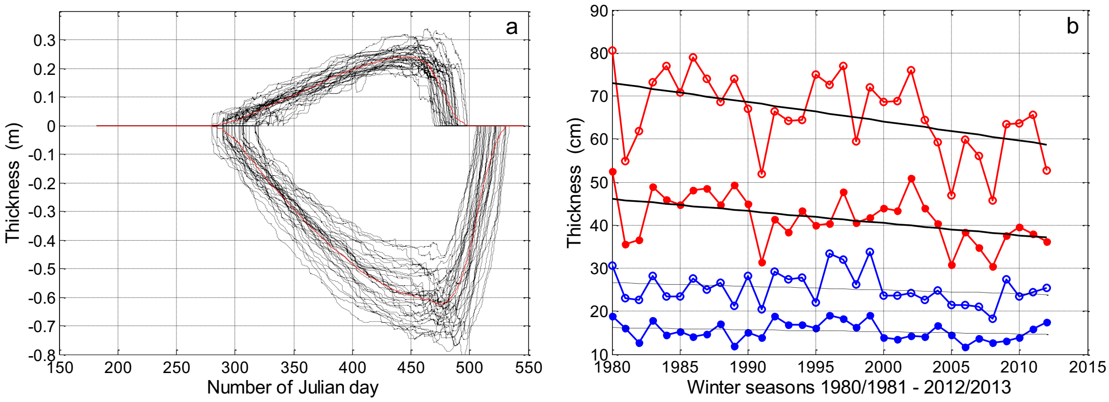

Figure 5. (a) Time series of modelled snow and ice thickness (black dotted lines) for 33 ice seasons (1980/1981 -2012/2013). The red lines are average thicknesses of snow (upper) and ice. (b) Inter-annual variations of modelled maximum (circles-connected) and average (dots-connected) snow (blue) and ice (red) thicknesses. The black lines are linear trends (solid line: $P<0.05$; broken line: $P>0.05$).

Table2. The statistical analyses (correlation coefficient and significance testing) between modeled snow and ice parameters. The red numbers showed the two variables reached significance level ($P < 0.05$).

	H_{save}	H_{iave}	H_{gi}	H_{ci}	H_{imax}	H_{smax}	*FD*	*SFD*	*IFD*	H_{ibot}	*OSMD*
H_{save}		0.19	0.79	-0.45	0.25	0.77	-0.10	0.62	0.45	-0.45	0.49
H_{iave}			-0.16	0.75	0.90	0.48	0.03	0.12	0.41	0.75	-0.24
H_{gi}				-0.72	0.11	0.57	-0.11	0.68	0.46	-0.71	0.68
H_{ci}					0.61	-0.06	0.03	-0.32	0.05	1.000	-0.55
H_{imax}						0.55	-0.09	0.31	0.58	0.61	-0.01
H_{smax}							-0.13	0.51	0.53	-0.06	0.38
FD								-0.09	-0.04	0.02	-0.14
SFD									0.78	-0.32	0.63
IFD										0.05	0.43
H_{ibot}											-0.54
OSMD											

H_{save}: average snow thickness; H_{iave}: average ice thickness; H_{gi}: granular ice thickness; H_{ci}: columnar ice thickness; H_{imax}; maximum ice thickness; H_{smax}: maximum snow thickness; FD: freeze up date; SFD: snow free date; IFS: ice free date; OSMD: onset snow melting date.

The modelled maximum ice thickness and portion of columnar ice and granular ice suggested that in the 80s, the columnar ice composes the major ice floe because cold winter may subject to less snowfall and ice formation is caused by freezing of lake water mainly. In 90s, the granular ice became more important to the total ice floe most likely due to more snow available to form snow-ice and superimposed ice. After 2000, the formation of columnar ice is more than that of the granular ice, but in recent years (since 2006) the granular ice formation has an increasing trend. The statistical analyses between various modelled snow and ice parameters are summarized in the Table 2. From this Table, one can see potential linkages between modelled snow and ice parameters and this will be a starting point for multiple regression analyses of key model output and their significance explaining weather forcing factors.

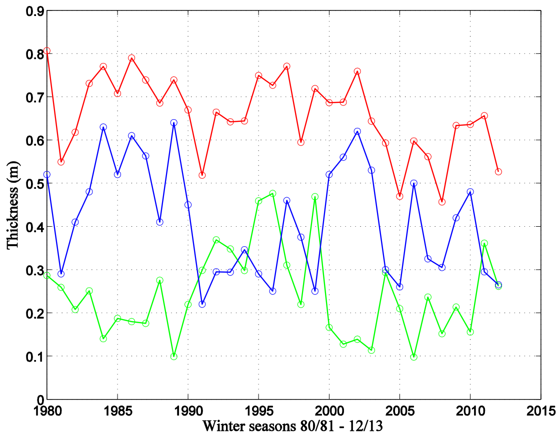

Figure 5. The inter-annual variation of maximum modelled total (red), columnar (blue) and grandular (green) ice.

5 Conclusions

The impact of weather forcing on inter-annual variation of snow and ice thickness in Orajärvi lake was investigate. The temperature showed a clear increasing trend in freezing season (FS). The total precipitation has no clear trend although a large inter-annual variation was seen. The snow precipitation has no significant trend according to our criteria to separate snowfall from total precipitation. However, the snow thickness measured in land showed a decreasing trend ($P > 0.05$) roughly 8mm/10yr. This could probably link with the increasing of air temperature.

The HIGHTSI model can produce reasonable snow and ice parameters. The relation between air temperature and freeze up date is strong (Palecki and Barry, 1986). The HIGHTSI modeled freeze up date can be regarded as the earliest possible lake freezing date. The modeled ice break up date is a theoretical value, which we refer to the latest possible final ice breakup date. In reality the final ice breakup data could be weeks earlier than this theoretical number because of wind effect. For sea ice condition, the final breakup may occur when ice flow was still 30 cm thick (Lei, et al, 2010). The modeled inter-annual variation of ice thickness has a decreasing trend, but no clearly trend for modeled snow thickness. The snowfall will contribute to the formation of granular ice (snow-ice or superimposed ice). A recent Orajärvi lake ice process modelling study suggested that granular ice can be 30% - 50% of the total ice thickness (Cheng et al, 2014). Our inter-annual variation of modelled granular ice supports such conclusion.

For extreme winter seasons (e.g. 91/92, 08/09), the calculated maximum lake ice thickness was coherent with the overall sea ice condition in the Baltic Sea (Patrick Eriksson, personal communication). This could explain that the weather forcing factor is the primary driving forcing for ice formation.

Our next step work is to apply stepwise multiple regression analyses method to identify the explaining variables (in this case the external weather forcing factors) on the basis of their significance degree from large to small into regression equation to investigate how the key model outputs (c.f. Table 2) linked with the potential external weather forcing factors. In order to find out best possible regression formulae, we need to carry out sustainable monitoring of the lake environment inter-annually.

Acknowledgements
This work was supported by the Academy of Finland (contract 259537). It is also part of "Nordic Snow Radar Experiment" project funded by ESA and FMI basic research on snow and ice thermodynamic modelling in connection to international collaboration with the NMEFC.

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