PhD Dissertation　(Summary)

博士論文（要約）

Studies on lake ice thickness evolution with emphasis on roles of snow at Lake Abashiri, Hokkaido, Japan

（北海道網走湖における湖氷の氷厚発達過程

および雪の役割に関する研究）

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Seasonal ice cover is characteristic of lakes located in boreal and temperate regions. Lakes affect the local climate and weather by modulating the temperature, wind, humidity and precipitation. Essentially lake ice prevents heat and momentum transfer between the atmosphere and the lake water through its insulating effect from winter to spring. If the lake is covered by snow, this influence is further strengthened due to the lower thermal conductivity of snow. Therefore the duration and growth processes of lake ice are important for understanding the local/regional winter climate. The seasonality of lake ice also influences the lake ecosystem and its biogeochemical properties. Furthermore, freezing lake-ice winter cover has an effect on social activities. Various fishing techniques with drills on ice-covered lakes have been developed, and lake-ice functions as infrastructure for transportation in winter. Frozen lakes are also used as venues for recreation. Thus, the properties and the growth processes of lake ice are very important for not only for understanding the local/regional winter climate, but also for social activities.

Several recent studies of global warming (IPCC 2013) have reported that lake-ice phenology (dates of freeze-up and break-up, ice-cover duration) has changed significantly worldwide. Conventionally, the freeze-up date is defined as the first date when a lake is completely ice-covered, whereas the break-up date is the first date when it is completely ice-free. The ice-cover duration is defined as the time between the freeze-up and break-up dates. According to Benson et al. (2012), the freeze-up date of 75 lakes in the Northern Hemisphere became later at a rate of 1.6 d/decade and the break-up date earlier at a rate of 1.9 d/decade over the period 1975/76 - 2005/06. For mid-latitude lake ice, there have been few phenology studies. So far, seasonally ice-covered lakes have been studied mainly for the North American and northern

European lakes, and little attention has been paid to the lakes at mid-latitudes in other regions.

This study aims to clarify the properties of lake ice at mid-latitudes, subject to relatively moderate air temperature, much snow, and abundant solar radiation even in winter, as contrasted with lakes at high latitudes. For this purpose, field observations were conducted at Lake Abashiri in Japan for three winters and a 1-D thermo-dynamical model was developed for predicting ice growth at Lake Abashiri. Using this model forced by meteorological datasets from Abashiri, the roles of snow in the ice thickening process were examined, and also ice phenology parameters were estimated and interannual trends at this lake were associated for the past 55-year period to compare with lakes at high latitudes.

Firstly, the lake ice properties were investigated at Lake Abashiri, Hokkaido, Japan, located at mid-latitudes (44.0N 144.2E) based on the observation in the 2012/13 winter. The results showed that the snow ice (SI) layer accounted for 29% to 73% of the total ice thickness, a much greater fraction than that for high latitude lakes (10-40%, Finland, Leppäranta, 2009). Based on the observations, a thermodynamic model that includes both formation processes of SI and congelation ice (CI) was developed. The model successfully reproduced the thicknesses observed.

Next, to confirm the observational results and verify the model, the follow-up campaigns were conducted throughout two additional winters (2014/15 and 2015/16). Based on the results obtained, the role of snow in ice thickening process was examined from numerical experiments with this model. The results are summarized as follows:

(1) Commonly, lake ice was composed of whitish SI and translucent CI, and the contribution of SI to total ice thickness was significant: 29-73% for 2012/13, 40-60%

for 2014/15 and 28-65 % for 2015/16.

(2) The model, which was developed based on the observational results in 2012/13, successfully reproduced the observed thicknesses of both SI and CI for 2014/15 and 2015/16 as well, showing the validity of the model under different meteorological conditions. It was also found that the model can reproduce the break-up date well, with an accuracy of a few days.

(3) The roles of snow in lake ice growth were examined from numerical experiments with this model by comparing h_i, h_{ci}, and h_{si} calculated for three cases: (i) snow accumulates with SI formation (control run); (ii) snow accumulates without SI formation; and (iii) no snow accumulates. Here, the thickness was denoted by h, using subscripts i, ci, and si for total ice, congelation ice and snow ice, respectively. The results obtained for these three winters support a hypothesis that snow works to mitigate the ice thickness variation caused by meteorological conditions, and it was shown that ice thickness is controlled more by snow depth than by air temperature.

Then, to further examine the validity of the model and the role of snow in the ice growth under various meteorological conditions, the calculation of h_i, h_{ci}, and h_{si} was extended for the past 16 years (2000/01 – 2015/16), during which MODIS images are available, to determine the freeze-up dates. The results were found to be consistent with those obtained from the field observations in the three winters, as shown below:

(4) h_i, h_{ci}, and h_{si} calculated in the model are consistent with the ice thickness records measured at the near shore region of the lake.

(5) There is a significant negative correlation between h_{si} and h_{ci}, indicating that snow works to moderate the change in h_{ci} through the formation of SI. The importance of snow was also endorsed by the fact that h_i has a higher correlation with snow depth than

with air temperature at Abashiri.

Furthermore, to estimate ice phenology parameters and their interannual trends at this lake for comparison with other lakes in the northern hemisphere, the calculation was extended for the past 55-year period (1961/62 – 2015/16), using our model. In the calculation, the freeze-up dates were inferred from the air temperature data at Abashiri, and the break-up dates were calculated with the model. The results are summarized as follows:

(6) The average freeze-up date, break-up date, and ice-cover duration were estimated as 12 December, 17 April, and 127 days, respectively. On average, h_{si} (16 cm) accounts for 37 % of h_i (43 cm), higher than about 30 % in Finland (Leppäranta, 2015).

(7) Statistical analysis showed that the break-up dates have experienced a significant negative trend of -1.71 d/decade for the past 55 years, i.e. the break-up date has become earlier by 9 days for the recent half century. This trend is comparable with the trend for other lakes in the Northern Hemisphere for the 30-year period 1975/76 to 2004/05 reported by Benson et al. (2012). This is presumed to be because air temperature affected h_i more strongly due to less snow before 2000 compared with that after 2001. Time series for normalized anomalies of ice phenology parameters and air temperature showed that they are highly correlated, which is consistent with the result reported for the lakes in Europe and North America. On the other hand, the freeze-up dates did not show a significant trend for the 55-year period. The reason why the trend of freeze-up date at Lake Abashiri is less prominent than that of break-up date is considered to be firstly because the increasing trend of air temperature is twice as strong in March as in November to December and secondly because freeze-up date is affected not only by air temperature but also by lake-specific characteristics which determine the lake heat

storage, as discussed in Benson et al. (2012). As for h_i on 15 February, a significant decreasing trend (-1.4 cm/decade) was found, along with a much higher correlation with h_{si} than with h_{ci}. The observed negative correlation between h_{si} and h_{ci} supports our hypothesis about the roles of snow.

In this study, the properties of lake ice at Lake Abashiri were investigated as a case study for the lakes at mid-latitudes. As a result, it was shown that the main role of snow in ice growth is to mitigate the variability of ice thickness caused by the change in meteorological conditions, and ice thickness is found to be more strongly affected by snow depth than by air temperature. Although the study is limited to a specific regional lake, the obtained results are expected to apply to other lakes where meteorological conditions are similar, irrespective of latitude. Given that air temperature is predicted to become higher along with enhanced snowfall at high latitudes in the future, the results obtained here might serve to understand the changes in lake ice properties there. In addition, in light of the fact that SI formation is regarded as one of the most important growth processes of sea ice, especially in the Antarctic, the results are also expected to contribute to broader understanding in this domain.

Although many lake ice properties at mid-latitudes were revealed through this work, some details of the processes of snow ice formation and melting still remain unresolved. Further studies including field observation are required.