Predicting the effects of climate warming in the snow-covered, soil-freezing region and their impacts on agriculture（Abstract of the Final Report）

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1. Introduction

Eastern Hokkaido is one of the largest agricultural regions in Japan. Low air temperature and relatively thin snow covers on the ground cause the topsoil to freeze over winter in this region. Frozen soil generally has low ability to transmit water because pores are blocked by ice crystals. As a result a substantial portion of snowmelt flows overland (snowmelt runoff) without infiltrating into the soil. Snowmelt runoff may transport dissolved and suspended matters off the agricultural land, resulting in the loss of nutrients from the farms and the deterioration of water quality in streams and lakes. Frozen soil also delays seeds germination, thereby shortening the growing season. Despite the importance of frozen soil, very few comprehensive hydrological studies were conducted in this region until recent years.

In our Memuro study sites in the Tokachi region of Hokkaido, frost depths have significantly declined in recent years. The Intergovenmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4) concluded that average air temperatures in cold regions have increased at higher rates than the global mean during the second half of the 20th Century[1). According to IPCC-AR4, agricultural productivity in cold region will be increase due to global warming[2)], however in our study regions, we have observed indications that climate change may be related to increasing weed problems, crop damages caused by diseases and pests, and changes in the transport of soil water and nitrogen due to a decreased magnitude of upward water flux in winter that is driven by soil frost. Therefore, effects of climatic variability on soil frost have major implications on agricultural practices, but we have little scientific knowledge about the effects of climate change on frost depth in this region. In this study, we will; A) examine whether or not the soil frost will continue to decline, B) quantify the effects of climate change on soil frost and the flow of soil water under freezing conditions, and C) develop methods to evaluate these processes and their impact on agriculture, which are applicable to cold regions around the world.

2. Research Objective

The study objectives are to (1) compile a long-term and regional database of soil frost and snow depths in eastern Hokkaido, (2) conduct a detailed field study of soil freezing, thawing, and snowmelt infiltration under different soil freezing conditions, (3) understand the processes causing the recent decline of frost depth and examine the feasibility of forecasting soil freezing condition at seasonal or inter-annual time scale, and (4) evaluate effects of global warming on agriculture in regions having significant snow and soil frost.

3. Results

(1) Compilation of a long-term and regional database of soil frost and snow depths in eastern Hokkaido

(1.1) Summary of snow and frost depth observation by agricultural organizations in eastern Hokkaido

We discovered the historic snow and frost depths data collected by agricultural organizations at more than 90 points, which were previously known only to the local agricultural personnel. We obtained the data from 60 points in the Tokachi District and more than 30 points from the Kushiro-Nemuro (hereafter Konsen) District, some of which had more than 20 years of data. These numbers are nearly four times higher the number of AMeDAS stations with snow depth data.

(1.2) Long-term trends of soil frost depth in eastern Hokkaido

To examine the long-term trend of soil frost depth in the entire eastern Hokkaido region, we analyzed the frost depth data from 21 points with more than 20-years of records (see above). We also calculated the soil freezing index [3], which approximates frost depth, for 24 AMeDAS stations (or weather stations in pre-AMeDAS time) in eastern Hokkaido using the 30-50 years of temperature and snow depth data. The analysis showed that the reduction in frost depth since the late 1980's is wide spread in eastern Hokkaido except for the coastal areas of Kushiro and Nemuro. The reduction is due to thermal insulation of soil by snow cover in early winter due to earlier snow accumulation, rather than increases in temperature[3].

(1.3) Development and testing of the model to estimate soil frost depth

We developed a frost-depth model[4][5], which can relatively easily calculate the long-term trend of soil frost depth, and serves as a tool for spatio-temporal data interpolation and for the prediction under the climate warming. The model was parameterized using the field data from the Memuro research site in Tokachi, and subsequently validated using the data from Konsen Agricultural Experimental Station. The model requires only daily air temperature and snow depth as input data, allowing it to be froced with the climate model outputs for the prediction of future trends. The model strikes a balance between simplicity and accuracy. The validation results showed that the model can estimate the long-term trend of frost depth within a few cm of accuracy.

(1.4) Estimation of the long-term trend of frost depth

The model (see above) was used to calculate the long-term trend of annual maximum frost depths for 1978-2007 for 24 AMeDAS stations in eastern Hokkaido, 1892-2007 for the Obihiro weather station in Tokachi, and 1940-2007 for the Nakashibetsu weather station in Nemuro. The calculation showed that the reduction in soil frost since the late 1980’s is the first phenomenon since the settlement of Hokkaido, implying that the phenomenon may be having a major influence on the agricultural environment.

(2) Establishment of long-term monitoring system and measurement of soil water flux under freezing condition

The objective of this sub-theme is to investigate the effect of changes in frost depth on soil water regime of upland cropping systems by measuring soil water movement associated with the development of a frozen soil layer. According to the analysis of the data from the long-term field observation since 2001, it was shown that the frozen layer of about 20 cm thickness, which is the maximum frost depth in recent central Tokachi district, do not impede the snowmelt infiltration to the frozen ground[6)].

A new, paired-plot soil water monitoring site was established in 2005, where the development of a frozen soil layer was artificially enhanced by removing snow in the treatment plot and the natural condition was maintained in the control plot. The soil water movement was monitored continuously at both plots. Significant differences were observed throughout the winter seasons. The amount of water moved from deeper soil layer to frozen layer in the treatment plot was about two times larger than that at the control plot at the depth of around 50 cm, which is the maximum frost depth in the treatment plot. Soil water content in the surface layer at the treatment plot increased to near saturation after snowmelt period, although the soil at the control plot was not saturated. At the treatment plot, the infiltration rate of soil water at the bottom of the frozen layer was smaller than the rate of snowmelt during the snowmelt period, suggesting that the higher soil water content in the surface layer was induced by lower rates of infiltration through the well-developed frozen layer underneath.

(3) Processes causing soil-frost reduction, and feasibility of seasonal and inter-annual

prediction of soil freezing condition

(3.1) Relationship between frost-depth reduction in eastern Hokkaido and other snow and ice phenomena in Japan, and the cause of snowfall variability

The reduction of frost depth started in the late 1980's, coinciding with the reduction in snow accumulation depth in the plains area of Hokuriku region and the reduction in drift ice sighting along the Okhotsk Sea coast[3]. We also analyzed the cause of inter-annual variability in snowfall, which has a strong influence on frost depth. In eastern Hokkaido, located east of the "backbone" mountain range of Hidaka, snowfall is predominantly caused by the passing of extratropical cyclones during the weakening of "west-high, east-low" synoptic pattern. This is in contrast to snowfall in the Japan Sea coast, which is predominantly caused by the winter monsoon wind associated with the "west-high, east-low" pattern. The analysis of the occurrence of extratropical cyclones revealed that the frequency of cyclones was in an increasing trend in December, which is the critical month for the development of soil frost. Therefore, it is likely that the reduction in frost depth since the late 1980's is related to the increased frequency of extratropical cyclones associated with the weakening of the East Asian winter monsoon.

(3.2) Relationship between soil frost depth in eastern Hokkaido and El Ninõ - Southern Oscillation (ENSO)

We analyzed the climatic trends of frost depth in relation to ENSO, which is believed to be closely connected to climatic fluctuation and abnormal climate[7]. There was a significant relation ($p < 0.05$) between the annual maximum frost depth in eastern Hokkaido and the Southern Oscillation Index (SOI), which is considered an effective index of ENSO, after the late 1980's when the East Asian winter monsoon weakened (see above). The analysis also showed that the frost depth in 1993-2004 and sea surface temperature (SST) in northern Indonesia (2 ºN – 2 ºS, 122 ºE - 137 ºE) had a high correlation ($r^2 = 0.67$), almost at a level of predictability, meaning that it may be possible to predict the annual maximum frost depth in eastern Hokkaido from the SST in northern Indonesia in early winter (December).

(4) Long-range prediction and evaluation of agricultural impacts in regions affected by snow and frozen soil under global warming condition

(4.1) Evaluation of the prediction of snowfall and accumulation under climate warming scenarios.

Monthly maximum snow accumulation depth was estimated from the monthly temperature and precipitation data generated by the Meteorological Agency of Japan/Meteorological Research Institute Climate Scenario Ver. 2 (SRES-A2) using the method of Inoue and Yokoyama[8]. Further, daily data series were generated from monthly temperature and snow accumulation using the spline interpolation, and used as the predicted daily values under the warming scenario. The predicted values represent 20-year average, not individual years, for 1981-2000 (present), 2031-2050 (near future), and 2081-2000 (future). In the Tokachi Plain, the predicted temperature increases monotonically, whereas the predicted snow accumulation is small in the present, greatly increases in the near future, and decreases in the future.

(4.2) Prediction of soil frost depth in the Tokachi region under climate warming

The frost depth model (see above) was used to predict the spatial distribution of future frost depth in the Tokachi Plain for the area bounded by 42º 25’ - 43º 15’ N and 142º 52.5’ - 143º 37.5’ E with a spatial resolution of 10 km by 10 km. Frost depth decreases in 2031-2050 (near future) to a point of no frost due to the increase in snow accumulation that insulates the ground. In 2080-2100 (future), decrease in snow accumulation compensates for increase in temperature, resulting in a slight increase in frost depth. However, the frost depth in the future period is smaller, due to an increase in temperature. From the above, for assessing the impact of climate warming in soil frost depth, we need to consider two aspects: the long-term decreasing trend with the frost completely disappearing in the near future, and the reoccurrence of frost in the future. In addition to long-term climate trends, soil frost has substantial inter-annual variability depending to meteorological conditions. For example, if air temperature is above 0 ºC during a winter precipitation event in warmer climate, precipitation falls as rain, not snow, resulting in the lack of snow cover and enhanced soil frost (this actually happened in the winter of 2006-2007). Therefore, the general concept of monotonous decrease in snow accumulation and frost depth in cold regions may not applicable to eastern Hokkaido, meaning that it is necessary to evaluate the agricultural adaptation strategies considering the predicted changes in snow accumulation and frost depth.

(4.3) Assessment of climate-warming impacts on the agriculture and agricultural environment in eastern Hokkaido.

The reduction in frost depth means a milder winter condition and warmer soil, which has some positive effects on agricultural production. However, it also has negative effects on agricultural environment such as the occurrence of pest problems, risk of groundwater contamination by fertilizer, and unexpected occurrence of soil frost and crop damage in warm winters as experienced in 2006-2007. These negative effects on environments may negatively impact agricultural productivity as well. Therefore, it is important to balance the increased productivity and the environmental conservation.

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