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Report

JAPANESE GLACIOLOGICAL ACTIVITIES IN THE ARCTIC REGION

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Abstract: The objectives of the Japanese Arctic Glaciological Expedition were to study the regional characteristics of glacier processes and the climatic and environmental changes for the last few hundred years in the Arctic cryosphere. During 1987–1996, glaciological observation and shallow ice core drilling were carried out at various places such as the Greenland Ice Sheet, Svalbard archipelago and the main land of Norway.

1. Introduction

The first period research project concentrated on "Comparative studies on glacierization using snow and ice cores" as a basic cryosphere research subject to clarify the regional characteristics of glaciers distributed in the Arctic region. The second period research project which followed it emphasized "Mutual atmosphere-cryosphere interactions and their fluctuations". "Mutual atmosphere-cryosphere interactions" include movements of various substances in the falling of rain and snow and in the subsequent metamorphosis and conversion to ice of the accumulated snow, and in the snow melting process in the accumulated snow layer.

From the view point of climate characteristics of the Arctic cryosphere, this is considered an extremely important research subject.

The 3rd period research, which ended with observations in the 1995 fiscal year, covers the topic "Climate-environment signals that indicate cryosphere fluctuations". This includes study of characteristics of climate and environment signals in the Arctic and the regional distribution of their appearance.

Japanese glaciologists have been conducting observations in the Antarctic Ice Sheet, emphasizing the structure and fluctuations of the ice and snow environment, since the latter half of the 1960s. In the clarification of wide-area environmental fluctuations using ice and snow cores, we believe that comparison of the various types of indicator signals in the ice and snow layer between the two polar regions is necessary. Seen from this view point, since the distribution of oceans and continents in the Arctic, with an ocean surrounded by land, is opposite to that in the Antarctic, so that the geographical distribution of ice and snow is nonuniform, it is possible to use the differences in climate characteristics arising from this nonuniform distribution to clarify the transport processes of various substances in the atmosphere.

In addition, such causes as the consumption of large amounts of fossil fuel since the industrial revolution, and the production, and subsequent release into the atmosphere, of large amounts of anthropogenic substances accompanying the recent increase in economic activity, are now seriously affecting the global environment in ways such as global warming and acidification of precipitation. In particular, there is a direct effect on the Arctic region. Many of the substances produced by these activities are transported by the atmospheric circulation from the principal sources in middle and low latitudes to the high latitudes of the Arctic and Antarctic regions, and are deposited in the ice and snow layers of Ice Sheet and glaciers as condensation nuclei, ice crystal nuclei or dry fallout. The vertical profiles of composition ratios and concentrations of these substances seen in the snow cover layers of the last several hundred years provide good data for clarifying the mechanisms of occurrence of various environmental fluctuation phenomena. In this sense, the cryospheres of the Arctic and Antarctic regions are excellent regions for monitoring of global environmental fluctuation .

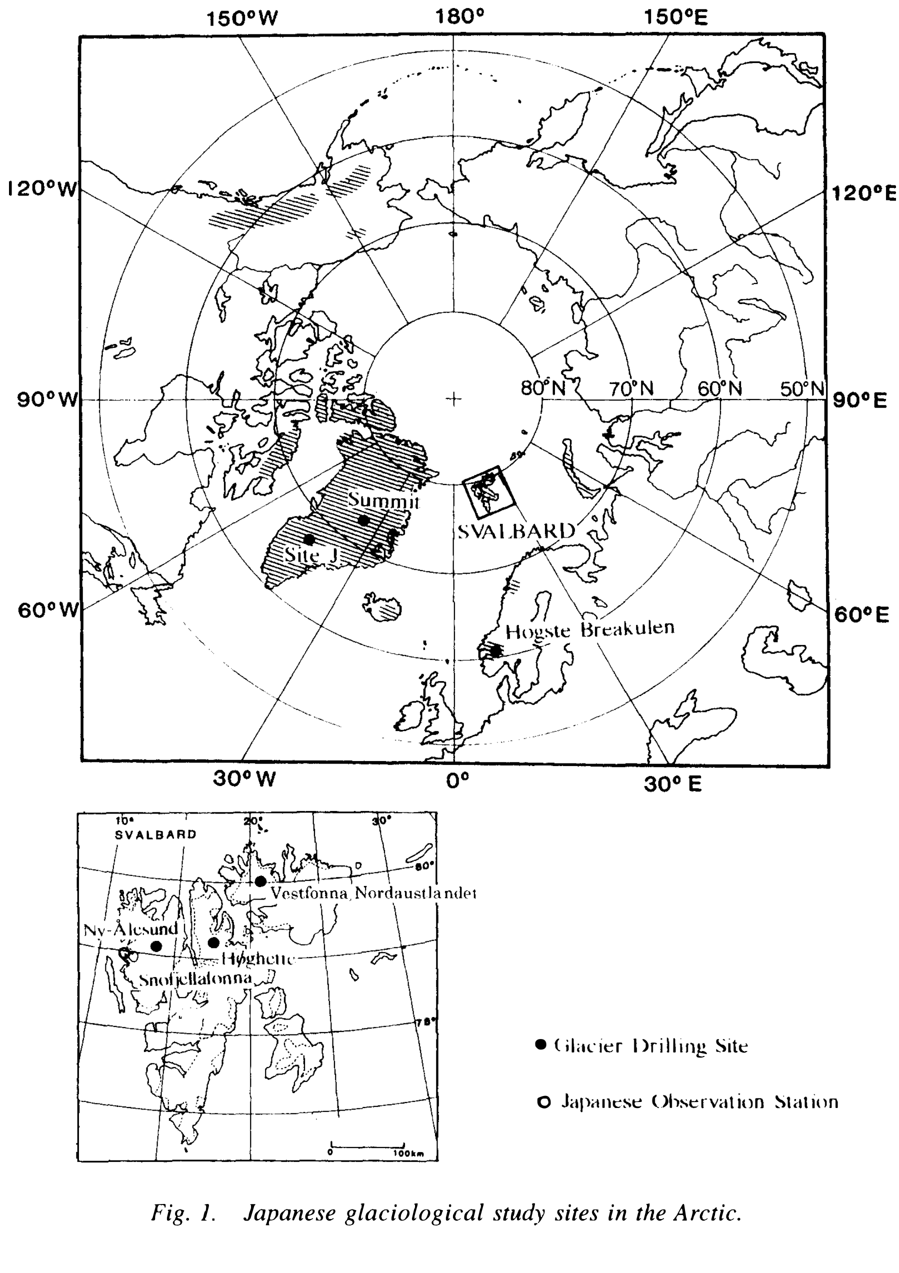

Fig. 1. Japanese glaciological study sites in the Arctic.

2. Variation of Ice Core Signals

In these studies, while considering the regional characteristics of the Arctic cryospheric climate system, we have conducted field observations in various parts of the Arctic regions (Fig. 1, Table 1). The work included observations of the general characteristics of snow cover, conducted as basic research, and of the types, quantities and origins of environment and climate signals included in those layers; and we have sought to clarify the transport processes within the atmosphere and between the atmosphere and the cryosphere.

At the same time, we designed snow and ice core studies. By analyzing the vertical distributions of substances of various origins within the ice and snow cores, we can clarify the fluctuations of climate and atmospheric environment over the last several hundred years.

The cryosphere contains a variety of substances (indicator signals) from various origins that reflect the state of the climate and environment. The types of signals and their combinations are indicators of the regional characteristics of the climate system and the depositional environment in the regions where they occur.

These climate and environment indicator signals can be roughly classified as follows.

i) Phenomena that show seasonal and secular fluctuations: Typical signals of this type are the composition of stable isotopes in water and the concentrations of certain ions; their seasonal variations permit years to be counted, and their secular variations permit reproduction of fluctuations in air temperature and precipitation amount.

ii) Regular and irregular variations of climatic and environmental states: Quantities of air bubbles in ice and snow cores and the composition of trace atmospheric constituents

Table 1. Coring list of JAGE (coring depth).

1987 May, (46.9 m), Norway, Jostedalsbreen	
61°43′N, 7°08′E, elevation: 1960 m	(J)
1987 June, (85.9 m), Svalbard, Hoghetta Ice Cap	
79°17′N, 16°50′E, elevation: 1200 m	(H)
1989 May–June, (206 m+101m), Greenland, Site-J	
66°52′N, 46°16′W, elevation: 2030 m	
1991 July–August, Deep Drilling Test I	
Greenland Summit, GRIP Camp	
72°34′N, 37°37′W, elevation: 3230 m	
1992 June–July, Deep Drilling Test II	
Greenland Summit, GRIP Camp	
72°34′N, 37°37′W, elevation: 3230 m	
1992 July, (84 m+24 m), Svalbard, Snofjellafonna	
79°08′N, 13°19′W, elevation: 1160 m	(S)
1993 June, (185 m+49 m), Svalbard, Asgardfonna	
79°27′N, 16°43′W, elevation: 1140 m	(A)
1994 September, (10 m), Svalbard, Bregerbreen	
78°54′N, 11°50′E, elevation: 450 m	(B)
1995 May–June, (210 m), Svalbard, Vestfonna	
79°58′N, 21°01′E, elevation: 600 m	(V)

found in them; fluctuations of amounts of carbon dioxide, methane, etc.; variations of amounts and composition of microscopic particles, etc.
iii) Sudden and artificially produced rapid variations: Fallout of debris from volcanic eruptions and of radioactive substances from nuclear tests are typical of this category and are used as index layers of the years in which they occurred.
In a high latitude region such as the Arctic region, the atmospheric general circulation concentrates substances emitted in the low and middle latitude areas and finally dumps them, making this an ideal region to obtain global-scale atmospheric background information.

3. Glaciological Setting of Observed Area

3.1. Ice and snow observations in the Svalbard archipelago

The Svalbard archipelago, located at 77° to 81°N, is at the same latitude as Greenland, but it is only at the limit of the sea ice region, which is pushed northward by the Gulf Stream, and the climate is relatively mild, with the ocean to the west always open. During the ice ages the ice covered area expanded in this region; according to one theory, it was connected to the European (Eurasian) Ice Sheet across the Barents Sea.

The area of the Svalbard archipelago is 62000 km^2, 60% of which is covered by glaciers. The height distribution of the glacial equilibrium line reflects the distribution of precipitation; it is low on the west coast and high in the interior. The present icefield stretches out at an altitude of 1000 m and the ice flows into the surrounding fjords. Even though these glaciers are at high latitude, they are presumed to be of subpolar type in glacier classification; during the melting season melt water appears even in their accumulation areas and penetrates to the lower layers of the glaciers so that sometimes the structure and chemical composition in the previous accumulation layer is disrupted. Until now it has been believed that so-called "wet" ice cores are not suitable for reproducing past climates and environments, so little research has been done on them.

However, reference levels indicating specific years such as artificial radioactive substances from nuclear tests and fallout from volcanic activities are well preserved in the ice cores, and depending on the type of substance there is a good possibility that signals remain even in the oldest deposition layer. By the use of suitable substance detection and detection methods, it is perhaps possible to find signals that permit the climate and environment to be reproduced.

From these ice and snow environment characteristics, a systematic observation program to research the existence of aerosols and solid particles in the atmosphere over the Svalbard archipelago, and the mechanism by which they become fixed in the ice as core signals through mixing into the snow cover layer, metamorphosis of the accumulated snow and its conversion to ice, was formulated, and observations were started from 1987.

In 1990 the National Institute of Polar Research (NIPR), Arctic Environment Research Center (AERC) established an observation station at Ny-Ålesund, on the western coast of Spitsbergen, the largest island in the Svalbard archipelago, and started observations. Long-term observations of fluctuations in the chemical and isotopic composition of snow falling in winter and the amounts of aerosols in the atmosphere have been conducted here. The station is located near the Brøgger Glacier, where Norwegian researchers have conducted observations of mass balance over the past 30 years. The location is suitable for observations of glacial hydrology, metamorphosis processes in accumulated snow and glacial biology, and many glaciological observations have been carried out in these fields.

3.2. Glaciological observations on the Greenland Ice Sheet

The island of Greenland, site of the only Ice Sheet that has survived into the post-glacial period in the Northern Hemisphere, has an area of 2186000 km^2, of which 79%, is covered by the Ice Sheet. The average altitude of the Ice Sheet is 2135 m, and its average ice thickness is 1515 m, so that it contains 9% of the fresh water on earth; its scale is about 1/10 that of the Antarctic Ice Sheet. The annual average precipitation on the Ice Sheet is the equivalent of 36.7 cm of water; the mass balance of the Ice Sheet is believed to be slightly positive.

Ice Sheet core studies by Japanese researchers started at site J on the midsection of the west coast, at 66.9°N, 46.2°E, in 1989. An ice-snow core was taken to a depth of 200 m near the dry snow line, from it the climatic and atmospheric environment fluctuations over the last 450 years have been reproduced.

4. Some Research Results

4.1. Movement of substances in the snow layer on the Brøgger Glacier

According to observations of seasonal variations of concentrations of the principal chemical constituents and the isotopic composition in the accumulated snow layer on the glacier surface (GOTO-AZUMA *et al.*, 1993), the concentrations of the main chemical constituents are one order smaller in summer than in winter. In addition, in the upper part of the superimposed ice in the lower part of the accumulated snow layer, what is believed to be a "redistribution peak" formed when ions are accumulated as the surface snow melts has been detected. This peak has also been detected in older layers; it is believed to be preserved in the glacier layer structure.

This is the "wash-out effect in the accumulated snow layer" that accompanies the infiltration of melt water; whereas, in winter, trace constituents that adhere to the surface of the fallen snow are taken into the accumulated snow layer relatively uniformly, it is believed that in summer the melt water washes these trace substances off of the ice particle surfaces, and they flow downward. This in turn indicates that more of these trace substances adhere to the surfaces of falling snow crystals than act as condensation nuclei of ice crystals or snow crystals.

4.2. Biological activities in glaciers

It has been confirmed that large quantities of micro-organisms, such as algae and bacteria, breed in the surface ice and snow layers of glaciers such as the Brøgger Glacier, and the Snofella Glacier to be discussed later. During the summer melting season, a variety of micro-organisms have been observed to breed in the surface snow and ice layers over nearly the whole area of these glaciers. The amounts, types and distributions of micro-organisms in the ice and snow layers differ according to altitude on the glacier.

It has become clear that single-celled green algae such as *Clamidomonas nivalis*, which is known as a snow alga, are mainly distributed in the glacial accumulation zone from 400 m to 1200 m, while filamentous blue algae of the genus *Formidium* and bacteria breed mainly in the glacial ablation zone; the quantity of micro-organisms increases rapidly with decreasing altitude.

This discovery has made it clear that even in glacial research in this region, it is necessary to consider a glacier as an ecological system including organisms. For example, it is possible that these biological activities can greatly affect the movement of substances and the mass balance of substances in the glacial ecological system.

4.3. Compound ice bodies seen in cores from the Høghetta Ice Cap on Spitsbergen

In this Ice Cap, at a depth of about 50 to 60 m out of the total thickness of 85m to bed rock, there is a major unconformity, with discontinuities in the quantity of air bubbles, crystal axis orientation distribution and solid particle concentration. The lower layer of the core contains algae, bacteria colonies and flower petals; carbon 14 dating gave an age of about 4000 to 6000 years. From estimate of the rate of accumulation in that area, the age of the glacier ice in the upper layer is estimated to be about 300 years, so that there is a hiatus of several thousand years between the upper and lower layers. It is possible that the ice in the lower layer is a remnant ice body of the glacier during the period of glacial retreat; and that a new glacier was formed on top of it by a glacial surge accompanying climatic fluctuation.

The age of the ice in the lower layer corresponds to a period of climatic warming in the post-glacial period called a hypsithermal interval. The scale of the glaciers in the Svalbard archipelago at that time was less than at present, and it is believed that the upper limit of vegetation was higher. For example, the algae and bacteria colonies in the lower layer of the core from the Høghetta Ice Cap, judging from their form and composition, are believed to be the same types as those that now breed on the surface of the ablation zone of the Brøgger Glacier. This indicates that at the time that the ice in this layer was deposited as snow (4000 to 6000 years ago), what is now the accumulation zone of the Høghetta Ice Cap (altitude 1200 m) had a climate about as warm as that of the ablation zone of the present Brøgger Glacier.

4.4. Radioactive substances in ice cores

Radioactive substances released on a large scale by nuclear bomb tests have been deposited in the snow layers of glaciers and ice sheets. Those radioactive substances were transported by the atmosphere, diffused and fell out, and were deposited and are preserved as reference snow layers in glaciers. These year index layers in the ice and snow can be used to estimate the amount of precipitation. The Svalbard archipelago is not an exception; peaks of gross β activity and ^{3}H have been detected in all of the glaciers in which observations have been made. That peak value is about 20 Bq/m^2·a. This value is less than the 400 Bq/m^2·a in the French Alps, but is about the same as the value observed in Greenland (PINGLOT *et al.*, 1994).

This difference has possibly come about because the radioactivity over the European continent was locally concentrated by air currents containing highly concentrated radioactive matter, but in the Svalbard archipelago and Greenland, the substances were deposited from an air mass that extended over the whole Arctic region.

Something similar happened in 1961–62. Perhaps because the Svalbard archipelago is near Novaya Zemlya, where Soviet nuclear tests were frequently conducted, high levels of 200 to 540 Bq/m^2 of Cs^{137}, 10 to 20 times the level from the Chernobyl accident, have been detected. In addition, in the vicinity of the glacial equilibrium line, there is a tendency for these radioactive isotopes to be concentrated by about a factor of 10; this is believed to be due to the effect of snow melt water.

4.5. Past climates inferred from the Site J core from Greenland

In May and June 1989, drilling was conducted at Site J, at an altitude of 2030 m on the Greenland Ice Sheet at 66°51.9′N, 46°15.9′W, and a 206.5 m deep core was obtained. From analysis of ice and melt water samples, it has been inferred that the layer at 206.5 m depth was deposited 450 years ago (the year 1540). The dating was done by a combination of the following methods: i) The combination of stable oxygen isotopes ($\delta^{18}O$) in the ice was measured, and the seasonal variations were counted going down from the surface. ii) The electrical conductivity (ECM) of the ice was measured to detect layers corresponding to specific volcanic eruptions. iii) A reference level of radioactive isotopes from nuclear bomb tests (*e.g.* the 1963 layer) was detected.

It is estimated that the average July temperature at Site J is –5°C (OHMURA, 1987). Since in the cold season ice starts to melt when the air temperature rises above –3°C, at Site J the surface snow melts in summer, and the melt water penetrates into the interior. When this melt water reaches a layer that is still at a lower temperature from winter cooling, it refreezes to form ice crust. In fact, at Site J 2804 layers of this ice crust were observed in the 206.5 m core.

The thickness of this ice crust is believed to reflect the amount of melt water; consequently, it is correlated with the amount of snow that melted at the surface snow. Measuring the distribution of thickness of the observed ice crust makes it possible to estimate the amount of melt water in summer at that point, hence the air temperatures in past summers.

Melt Feature Percentage (MFP, %) and oxygen isotope composition in the Site J core are analyzed. There were periods of unusually low MFP in 1690–1700 and 1830–1860; it is inferred that the summer air temperatures in these periods were unusually low. These correspond to periods in which glaciers advanced considerably in the European Alps; the Little Ice Age (1550 to 1850) also corresponds to a period of lower than normal air temperatures. In Japan, these periods are known as the times of the "Genroku Famine" and the "Tempo Famine", respectively, so it is inferred that the summer air temperatures were also below normal in Japan. Minima of the stable oxygen isotope compositions were also observed during these periods, also leading to an inference of low temperatures.

4.6. Acidification of precipitation in the Arctic since the industrial revolution

Since the Arctic is far removed from central areas of human activity, its environment has been assumed to have retained its pristine cleanliness, but since about 1970 facts which require this perception to be changed have been reported. One phenomenon is the so-called Arctic haze. Since there were not enough observations in the past, we must rely on the ice cores to learn when this pollution of the Arctic region started.

The concentrations of sulphate ions and nitrate ions at Site J in Greenland since 1700 are analyzed. The sulphate ion concentration started to increase from about 1850; it dropped briefly about 1930, then increased rapidly, reaching a maximum around 1970. The increase of nitrate ion concentration includes a component from volcanic activity, but the greater part of the trend is due to human activity. As made clear by analysis of cores from the Antarctic Ice Sheet, the carbon dioxide concentration started to increase considerably about this time. The drop of sulphate ion concentration around 1930 resulted from the drop in production activity due to the Great Depression. The falling trend of concentration since about 1970 agrees with the period in which the use of devices to remove sulphur from gaseous emissions became widespread.

Meanwhile, the nitrate ion concentration has been increasing since about 1780; the increase was gradual from about 1820 to about 1950, but after 1950 it started to increase rapidly, reaching a maximum about 1970. It is not clear whether the reason for the increasing trend from about 1780 lies in human activities or natural phenomena. The increase from about 1950 is believed to be due to atmospheric pollution from the spread of diesel engines.

These increases in the concentrations of sulphate ions and nitrate ions explain the increase in the acidity (decrease of pH) of precipitation. Compared to the background level before the Industrial Revolution, the acidity today has increased by a factor of 1.4 in Greenland and a factor of 2.0 in Svalbard. This spread of acidic substances from air pollution to the Arctic region has been accelerating since the Industrial Revolution, but the maxima of sulphate ion and nitrate ion concentrations about 1970 indicate that from that time atmospheric pollution has started to decrease somewhat.

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