Alpine ice-core drilling in the North Pacific region

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ABSTRACT. The Institute of Low Temperature Science at Hokkaido University conducted ice-core drilling in alpine glaciers in the northern North Pacific region to reconstruct climate change in this region for the past few hundred years. We drilled two ice cores in the Kamchatka Peninsula, Russia. An ice core with a length of 211 m was drilled on a glacier at the summit caldera of Ushkovsky mountain in 1998. A second core, with a length of 115 m (until bedrock was reached), was drilled on a glacier at the summit caldera of Ichinsky mountain in 2006. We drilled three further ice cores in Alaska, USA. Two ice cores with lengths of 50 and 212 m were drilled on a glacier at the summit caldera of Mount Wrangell in 2003 and 2004. The third ice core was drilled on the ice divide among three glaciers, Black Rapids, Trident and Susitna glaciers, which represent a flat saddle north of Aurora Peak in the Alaska Range. This paper details the field operations and characteristics of the different ice-drilling systems used and the problems encountered.

KEYWORDS: climate change, ice core, ice coring

INTRODUCTION

It has been proposed that the North Pacific climate has fluctuated widely in a decadal or inter-decadal cycle known as the Pacific Decadal Oscillation; this fluctuation is also referred to as a regime shift (e.g. Minobe, 1997; Shiraiwa and Yamaguchi, 2002). It has also been reported that the decadal or inter-decadal cycle appears not only in climate but also in marine ecological systems in the North Pacific (e.g. Mantua and others, 1997). However, details of the mechanism of the relationship between climate and marine ecological systems have not been identified. To reconstruct the changes in climate and environment in the North Pacific, we obtained several ice cores in this region. On the Asian side, we drilled in the Kamchatka Peninsula, Russia, at Ushkovsky mountain in 1998 and Ichinsky mountain in 2006 (Shiraiwa and others, 1999; Matoba and others, 2007). On the North American side, we drilled in Alaska, at Mount Wrangell in 2003 and 2004 and at the flat saddle north of Aurora Peak in 2008 (Shiraiwa and others, 2004; Yasunari and others, 2007; Tsushima and others, 2014).

In the mid- and low latitudes, suitable locations for ice-core drilling are limited to the high-elevation sites of alpine glaciers, where the effects of snowmelt in summer on chemical signals in ice cores are not significant. Generally, the transportation of equipment for drilling expeditions to these high-elevation sites is done by helicopters or airplanes with relatively small payloads. Therefore, lightweight and small-volume drills need to be used, and expeditions must be designed to operate with high levels of energy efficiency. Here we report on the drilling systems, drilling operations and the conditions of sites where we performed ice-core drillings in the northern North Pacific region.

DRILLING OPERATIONS

The site information for the drilling locations is summarized in Table 1. The expeditions in Kamchatka were collaborative projects with the Institute of Volcanology and Seismology at the Russian Academy of Sciences (IVS-RAS). At Mount Wrangell, collaboration was with the Geophysical Institute of the University of Alaska Fairbanks (GI-UAF) and IVS-RAS, and at Aurora Peak we collaborated with the Water and Environmental Research Center of the University of Alaska Fairbanks (WERC-UAF). The details of each drilling operation are described below.

Ushkovsky

Ushkovsky mountain is located in the eastern part of the Kamchatka Peninsula (Fig. 1). The caldera on its summit has a diameter of 4 km and is filled with glaciers. There are two craters, Gorshkov and Herz, at the highest part of the mountain. Ushkovsky mountain is an active volcano. Ice-core drilling was conducted in the center of Gorshkov crater in June 1998 (Shiraiwa and others, 2001).

We used an electromechanical ice-core drilling system developed by Geotech Co. Ltd (Nagoya, Japan). The specifications of the ice-drilling system are shown in Table 2. The generator used for drilling was a four-cycle, single-cylinder gasoline engine (3.5 kVA, model EF400, Yamaha, Iwata, Japan). For high-elevation use, we replaced the fuel

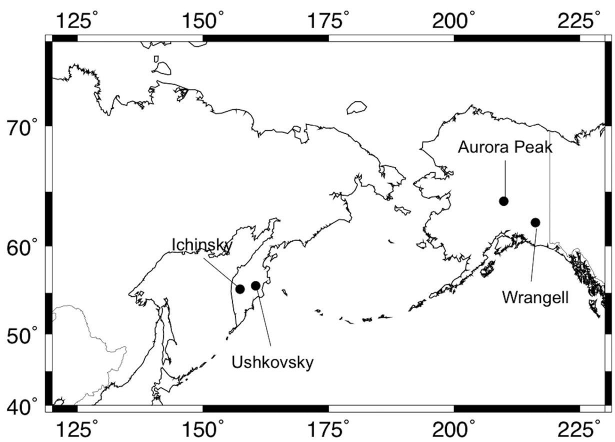

Fig. 1. Location map of the drilling sites.

Table 1. Information on drilling sites

	Kamchatka		Alaska	
	Ushkovsky[a]	Ichinsky[b]	Wrangell[c]	Aurora Peak[d]
Latitude	56°04′ N	55°46′ N	62°00′ N	63°32′ N
Longitude	160°28′ E	157°55′ E	144°00′ W	146°32′ W
Elevation (m a.s.l.)	3900	3600	4300	2800
Annual accumulation rate (m w.e. a^{-1})	0.56	0.68[e]	2.49–2.66[f]	1.8–3.1
10 m depth snow temperature (°C)	–15.8	–13.0	–18.9	–2.2
Glacier thickness (m)	~240	115	not available	252 ± 10[g]
Ice-core length (m)	212	115	50	180
Drilling year	1998	2006	2003	2008
Drill maker	Geotech Co. Ltd, Japan	Geotech Co. Ltd, Japan	ILTS, Hokkaido Univ., Japan	Geotech Co. Ltd, Japan

[a]Shiraiwa and others (2001); [b]Matoba and others (2007); [c]Shiraiwa and others (2004); [d]Tsushima and others (2014); [e]Matoba and others (2011); [f]Kanamori and others (2008); [g]Fukuda and others (2011).

spray nozzle in the carburettor with one with a smaller hole. It took a total of 103 hours over 12 days to drill down to 212 m. The typical diameter of the ice core was 94 mm, and the typical length was 1.0 m (firn) and 0.8 m (ice). The brittle ice zone was found at 140 m depth.

The drilling site was near several active volcanoes, so the ice cores contained large amounts of volcanic materials. We observed 328 volcanic ash layers in the ice core (Shiraiwa and others, 2001). The thickest ash layers were at least 10 mm thick. Therefore, the cutters and catchers were worn in each run that included volcanic ash layers and had to be sharpened frequently.

Ichinsky

Ichinsky mountain is located in the central part of the Kamchatka Peninsula (Fig. 1). On its summit is a caldera measuring 3 km × 5 km. The caldera is covered with an ice cap ~500 m in diameter. The most recent eruption occurred within the last 1800 years and at least several hundred years ago (Volynets and others, 1991). Glaciers flow from the caldera down both the steep northeast slope and the gentle southwest slope. Drilling operations were conducted at the center of the ice cap in August 2006 (Matoba and others, 2007).

We used an electromechanical ice-core drilling system developed by Geotech Co. Ltd (Fig. 2). The system was also used during an expedition to Belukha mountain in the Altai mountains, central Asia, in 2003 (Takeuchi and others, 2004). The drill was an improved version of a previous model used at Ushkovsky for high-elevation work (Takahashi, 1996). The barrel length was 1.35 m, shorter than the previous version (2.00 m), which reduced the operating space and made handling easier. The power of the drill motor was 0.35 kVA, less than in the previous version (0.6 kVA). The reducer was changed to a strain wave gear from a planetary gear. The power of the winch motor was the same as in the previous version. The armored cable was 4.7 mm in diameter, thinner than in the previous version (5.7 mm). The mast was changed to a fixed type from a tilting type. The specifications of the ice-drilling system are shown in Table 2. The generator for drilling was a four-cycle, single-cylinder gasoline engine (2.3 kVA, model EF2300i, Yamaha) with an inverter system of pulse width modulation control. For high-elevation use, we replaced the fuel spray nozzle in the carburettor with one with a smaller hole. To prevent the air intake from closing up because of a frozen air filter in the cold conditions, we removed the sponge air filter from the air filter unit. To prevent the carburettor from freezing, we attached a metal plate from the exhaust muffler to the carburettor, which conducted heat to the carburettor.

The total weight of the drilling system including a drill, mast and base unit, winch, and controller was 300 kg, which is 70 kg lighter than in the previous version. The shorter drilling length allowed us to operate in a small

Table 2. Specification of ice-drilling systems used at Ushkovsky, Ichinsky, Aurora Peak and Wrangell

	Ushkovsky	Ichinsky/Aurora Peak	Wrangell
Drill			
Diameter (outer/inner)	94 mm/125 mm	94 mm/125 mm	89 mm/110 mm
Core length	1.0 m (firn)/0.8 m (ice)	0.7 m (firn)/0.55 m (ice)	0.5 m (firn)
Drill/barrel length	3.02 m/2.0 m	2.13 m/1.35 m	2.1 m/1.4 m
Drill motor	200 V a.c./0.6 kVA	100 V a.c./0.35 kVA	100 V a.c./0.35 kVA
Anti-torque type	Pre-bent leaf spring	Pre-bent leaf spring	Pantographic
Specification of barrel	Applicable for both dry and liquid fill drilling	Dolphin-mount compatible	No jacket
Mast and winch system			
Mast type	Aluminum tilting tower	Aluminum fixed tower	Glass-fiber fixed tower
Mast height	3.5 m	2.3 m	2.3 m
Winch motor	200 V/0.75 kVA	100 V/0.75 kVA	100 V/0.72 kVA
Cable	Armored, diameter 5.7 mm	Armored, diameter 4.7 mm	Armored, diameter 5.7 mm
Manufacturer	Geotech Co. Ltd, Japan	Geotech Co. Ltd, Japan	ILTS, Hokkaido Univ., Japan

Fig. 2. Drill jacket and barrel of Geotech Co. Ltd used at Ichinsky and Aurora Peak.

Fig. 3. Drilling system of ILTS used at Mount Wrangell.

drilling tent, resulting in a reduction in the weight of the drill tent. The length of ice core obtained by one drill run with the shorter core barrel was also shorter (0.5 m). Shorter ice cores were easier to handle in terms of processing and packing. The shortened maintenance time in the drilling tent helped to prevent melting of the ice chips. However, we needed more drilling runs and a longer time to reach the deeper parts of the glacier. We estimated that the total consumption of fuel used for drilling was comparable to that when operating the previous version. The weight and volume of the fixed-type mast were lower than in the previous version. However, the reductions in weight and volume were balanced by the increased workload of the drillers on the snow surface. After the drill was drawn up, it had to be removed and laid onto the snow surface for the recovery of ice cores and to prepare it for the next run.

Wrangell

Mount Wrangell is located in southeastern Alaska. A glacier fills the 4 km $\times$ 6 km caldera at its summit (Fig. 1). Drilling operations were conducted at the center of the summit caldera in June 2003 and June 2004. Here we report on the 2003 expedition.

We used a lightweight electromechanical ice-core drilling system, which had been recently developed specifically for this expedition by the Institute of Low Temperature Science at Hokkaido University (ILTS-HU) (Fig. 3) (Shiraiwa and others, 2004). The specifications of the drill are shown in Table 2. The total weight of the system, which was composed of a drill motor part with anti-torques, a barrel, a cable and a drill controller, was 100 kg. The drill system had no jacket and had pantographic-type anti-torques, a half-round pulley on the top of the mast, and a drill mast that was used as the carrying case of the core barrel. The system required a 0.7 kVA generator. It took 22 hours over 4 days to drill to 50.3 m depth. The length of each ice core was ~0.50 m.

Aurora Peak

Aurora Peak is located in the Alaska Range, central Alaska (Fig. 1). Drilling operations were conducted in May and June 2008 in the flat saddle north of Aurora Peak, which constitutes an ice divide between Trident Glacier to the north and Black Rapids/Susitna Glacier to the south. The thickness measured using ice-penetrating radar was 252 ± 10 m, and the surface velocity at the drilling site, measured using GPS, was <0.5 m a^{-1} (Fukuda and others, 2011).

We traveled from Fairbanks to Delta Junction, the nearest runway to Aurora Peak, in cars carrying the equipment and six expedition members. We flew the personnel and equipment from Delta Junction to the drilling site on an airplane (DHC-3 Otter) supplied by Ultima Thule Outfitters. The total weight of the equipment was 1300 kg, including 200 kg of fuel. Four flights were required to transport all personnel and equipment.

The drilling system was the same as that used at Ichinsky mountain. We stopped drilling at 180 m due to restrictions on the length of the winch wire.

PROBLEMS ENCOUNTERED IN CUTTING COLD AND WARM ICE CORES AND THEIR SOLUTIONS

Figure 4 shows profiles of the drillhole temperature at the drilling sites. The ice was 'warm' at Aurora Peak. The ice temperature at 10 m depth was –2.2°C, and was more than –7°C from the surface to 180 m depth. The slipping of cutters at the bottom of the drillhole was a problem at Aurora Peak. During the cutting of warm ice cores, frictional heat was generated between the drill cutter and ice body, which melted ice chips. Water bearing ice chips was packed under the cutter, adhered to the concave section between the cutters and shoes, and easily penetrated into the hole of the screw bolt fixing. The packed water bearing the ice chips prevented the cutters from biting into the ice. To avoid this, we used a new drill cutter mount called a 'dolphin mount', which was designed for 'warm' glacier drilling (Takahashi, 2005) (Fig. 5). The cutter mount had no raised parts that could become stuck at the bottom of the cutter mount when the space contained ice chips. The height of the back part of the cutter was at the same level as the bottom of the cutter mount. A shoe is needed to control the cutting depth, although it is a raised part that creates problems. Therefore, a new shoe was

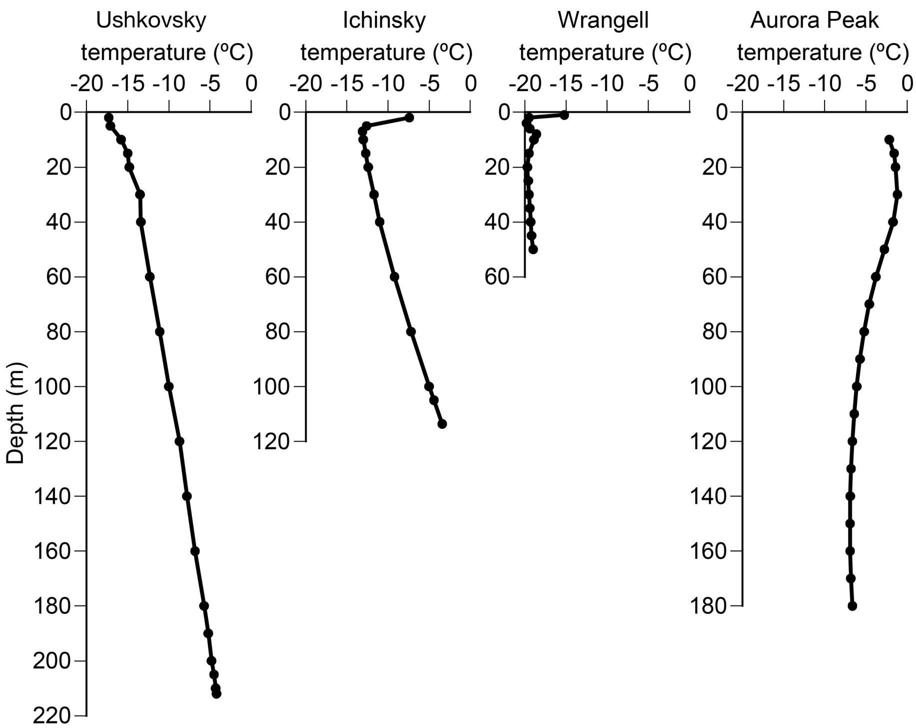

Fig. 4. Profiles of temperature of drilling hole at Ushkovsky, Ichinsky, Wrangell and Aurora Peak.

designed that was narrower than the width of the cutter mount. It was attached to the middle of the cutter mount rim, and ice chips were able to flow along the space beside the shoe. The cutting mount was coated with Teflon to reduce friction. This cutter mount worked well at Aurora Peak.

At Ichinsky, the air temperature in the drilling tent was >0°C. Thus, ice chips could easily melt on the drill during maintenance in the tent, and the meltwater then refroze onto the drill when the drill was reinserted into the drillhole. The refrozen ice caused various problems. Refrozen ice in the barrel scratched and broke the ice cores inside the barrel. Refrozen ice on the cutters and shoes caused slippage of the cutters at the bottom of the drillhole. To prevent such problems, we shortened the maintenance time in the tent and reinserted the drill into the borehole as quickly as possible before ice chips melted during maintenance.

Figure 6 shows the depth profile of a number of ice-core pieces and the total length of ice cores obtained by one drilling run at Aurora Peak. The number of ice-core pieces increased at depths below 150 m, and the average length of ice cores was ~0.5 m over the whole depth. This brittle-ice problem is well known and often appears below depths of 100–150 m in alpine glaciers or small ice caps (e.g. Takahashi, 1996; Koci, 2002). Below 100 m depth, the air pressure in bubbles in ice cores increases, leading to ice-core brittleness. However, brittle ice was not observed in the Ichinsky ice core, even though drilling reached bedrock,

Fig. 5. Photograph of 'dolphin mount'.

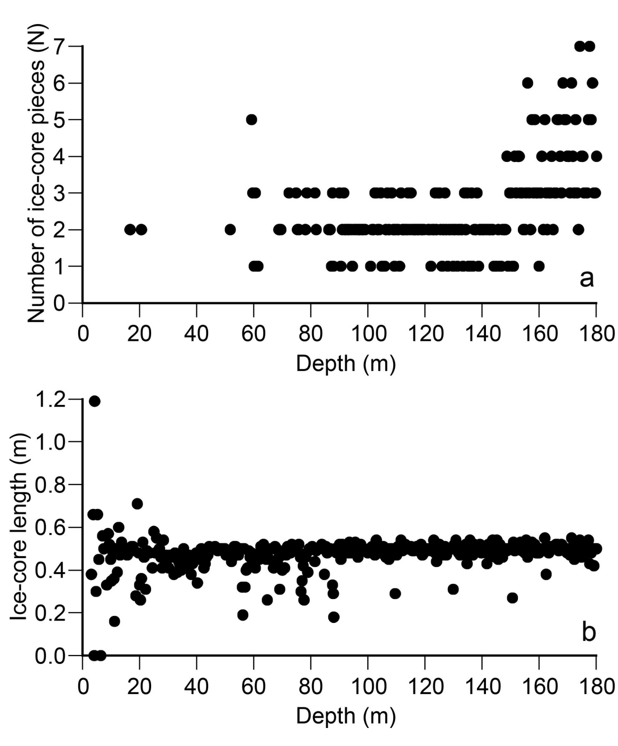

Fig. 6. Depth profiles of number of pieces of ice cores (a) and length of ice cores (b) obtained in each drilling run at Aurora Peak.

where the vertical strain rate increased substantially. Takahashi (1996) reported that another possible reason for brittle ice is an enhancement of the friction caused by ice chips penetrating into the space between the ice core and barrel. To avoid this problem, we attempted the following: (1) reducing the speed of cutter rotation to reduce shock to the ice core; (2) changing the cutter angle to make ice chips larger, making it more difficult for them to penetrate the space between the ice core and the barrel; (3) changing the shoe to reduce the drilling pitch. However, none of these modifications completely solved the problem.

SUMMARY

We have reported on drilling operations conducted on alpine glaciers in the northern North Pacific region. Two new lightweight drills were designed for use at high-elevation sites. In our expeditions, we encountered several problems with the drilling. Slipping of cutters at the bottom of the drillhole occurred at Aurora Peak. This resulted from the adherence of ice chips to the bottom of cutter mounts during warm ice cutting. To solve the problem, we used a new mount designed for warm ice, which worked well. Brittle ice appeared below depths of 150 m at Ushkovsky and Aurora Peak. We modified the process in several ways to avoid brittle ice cores, but we could not completely solve the problem.

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