Isotopic mass balance measurements of spray ice

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- Observation of spray icing
- Thin section, NMR imaging
- Cold laboratory experiment
- Estimation of Snow Mass Fraction

Spray ice is frozen ice formed from sea or lake spray water in cold regions and accreted on ships, offshore structures, and trees in lakeside, developing into a massive ice form.

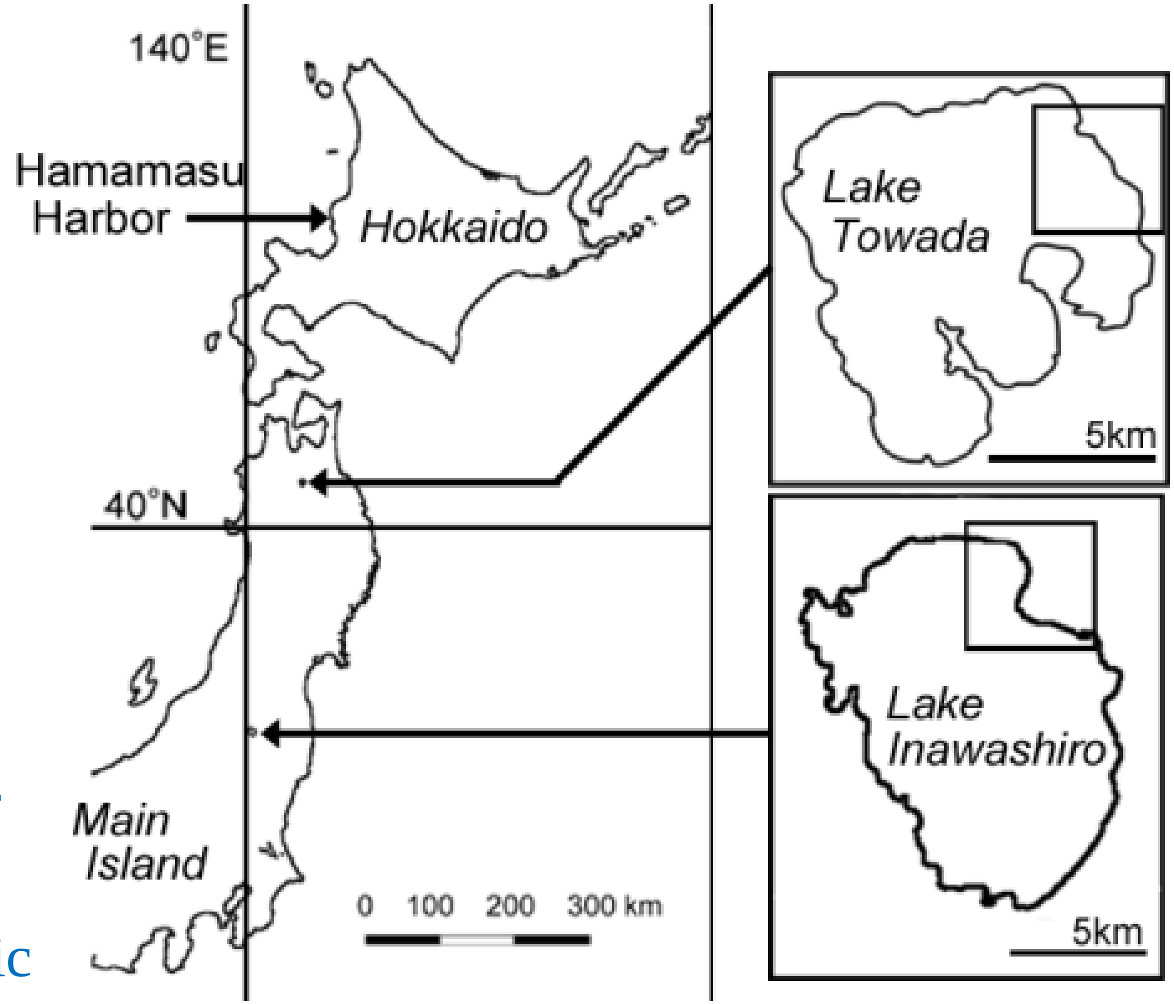
Freezing spray is the main cause of spray icing.

<u>Contribution of snow accretion?</u>

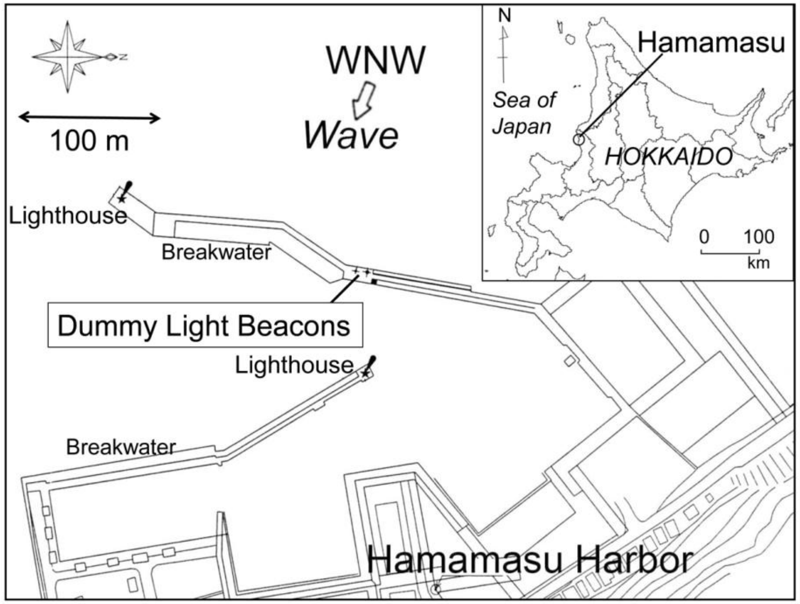
Spray ice accretion often occurs under intense snowfall.

The contribution of snow to spray icing is investigated using field observations and laboratory experiments.

- We collected samples of spray ice, snow, and water on the west coast of Hokkaido Island and in Lake Inawashiro and Lake Towada of Main Island, Japan.
- The structural characteristics of the spray ice were analyzed using conventional thin-section and NMR imaging.
- The snow mass fraction of the spray ice samples was calculated from the isotopic mass balance.



West coast of Hokkaido Island



High waves caused by north-westerly wind often generated a heavy spray jet at the dummy light beacons. The spray icing grew under heavy sea-water spray and during low temperatures.
Additionally, stormy weather often generated not only heavy spray jets, but also intense snowfall.

Thin section of sea spray ice

Layered structure of a sea-water spray ice sample in cross section.

The observed layering in the samples depends on the growth history of the spray ice.

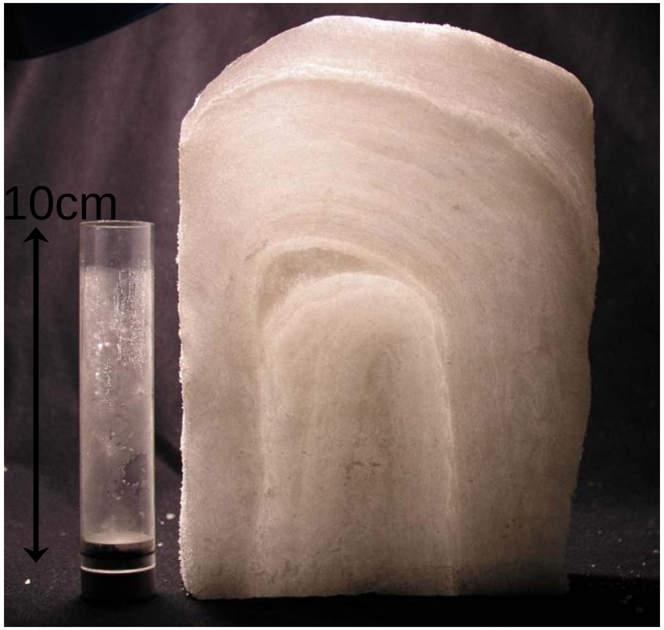
Additionally, the spray ice is composed of two ice types with different crystal structures:

- an ice layer with columnar ice.
- a granular layer with uniform, rounded smaller grains

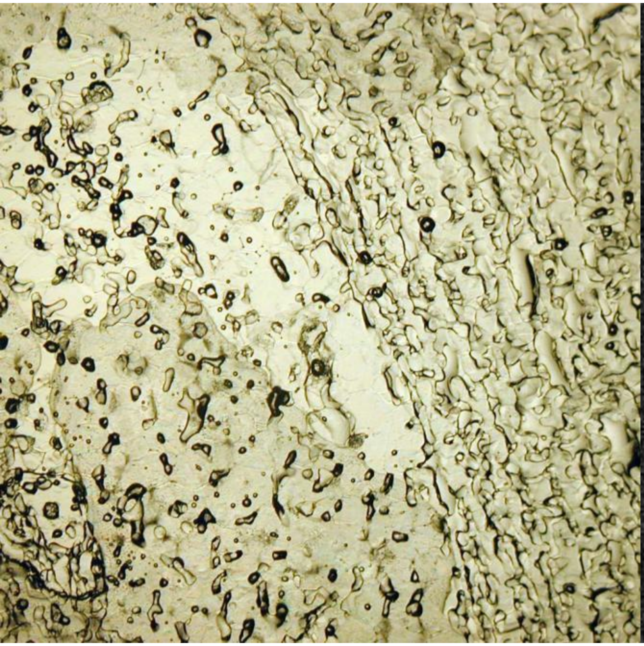
The differences in the ice composition may be caused by snow.

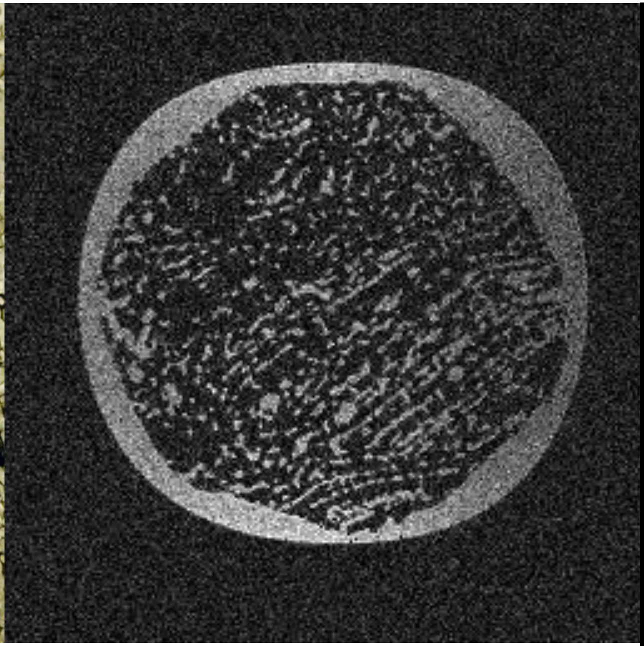
NMR Imaging of Sea Spray Icing

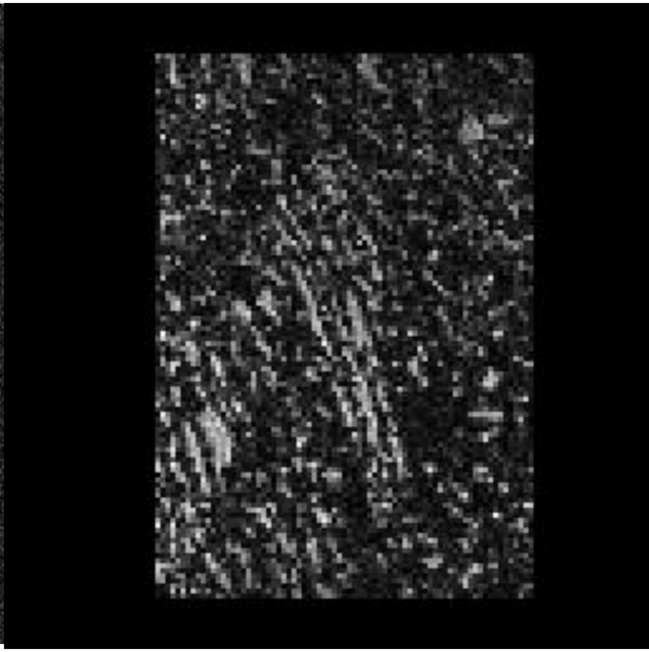
We have developed a compact NMR imaging system set up in a cold room to maintain the sample at a constant temperature.



The sea spray icing samples





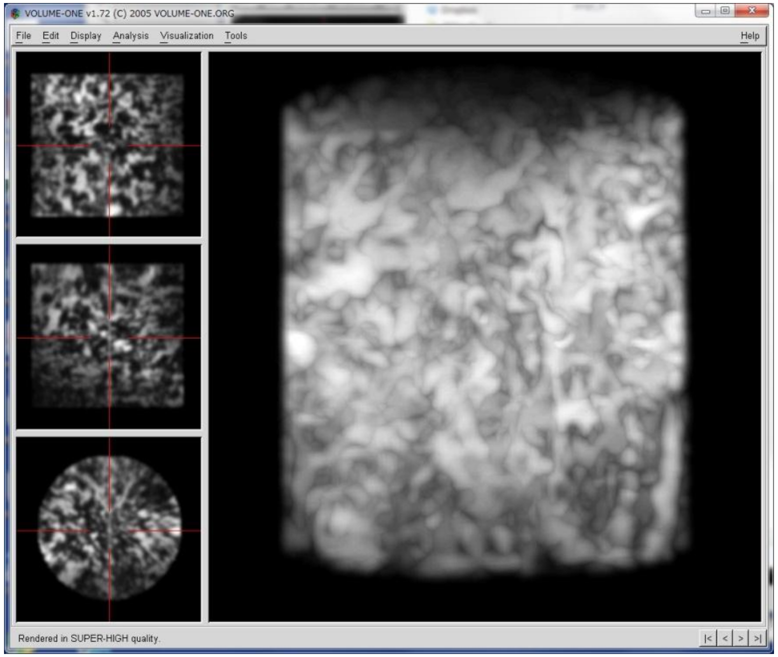


Conventional thin section of sea-spray icing sample

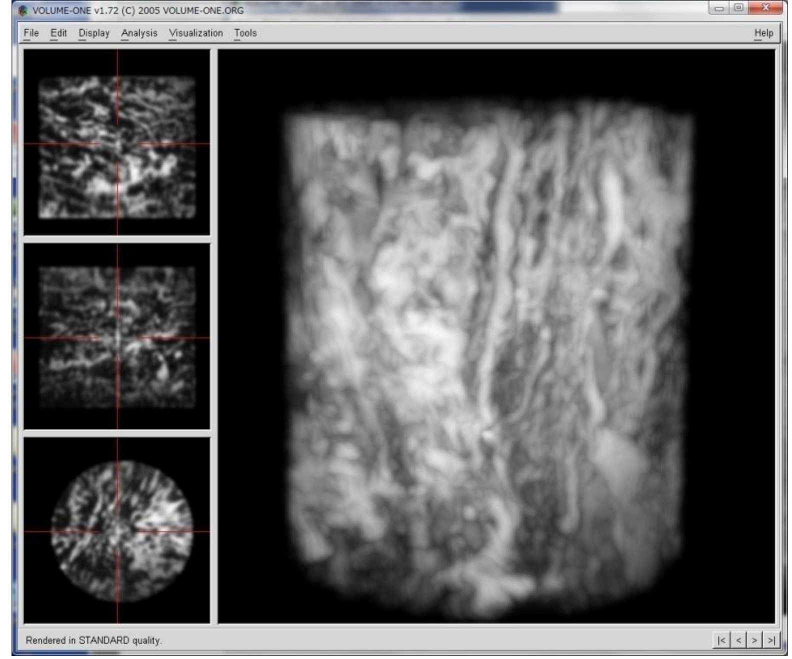
Image size (17 mm)^2

MR image of sea spray icing acquired from the 3D-SE sequence; image matrix size = 256 × 256, pixel size = (123 μm)^2, thickness = 123 μm, cylinder diameter = 24 mmΦ.

We used a suction pump to fill the air gaps in the drainage channels with dodecane ($C_{12}H_{26}$).



sample A 5mm ↔



sample B ↔

Vertical cross section of maximum intensity projection (MIP) view

Layered structure of a sea-water spray ice sample

Sample A

granular ice layer is dominant.

Sample B

Icy layer is dominant.

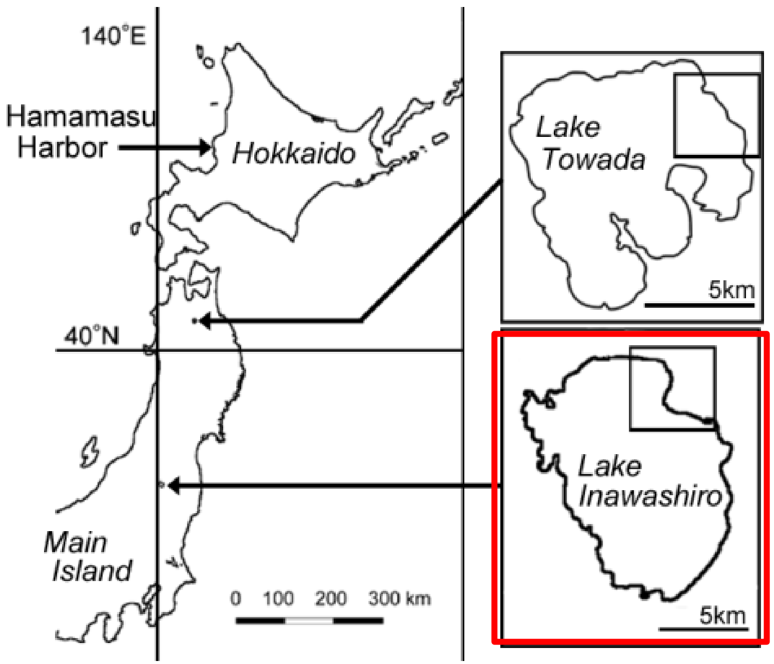
NMR imaging indicates that these layers have brine drainage channels.

→Salinity of the sample decrease with time.

Spray icing on trees beside lake

"Spray ice" is an interesting ice phenomenon in natural lakes, also observed around *Lake Inawashiro* and *Lake Towada*, Japan. It is a popular motif for photographs, and a tourist attraction.

Lake Inawashiro has an area of 100 km^2 and an average depth of 50 m.

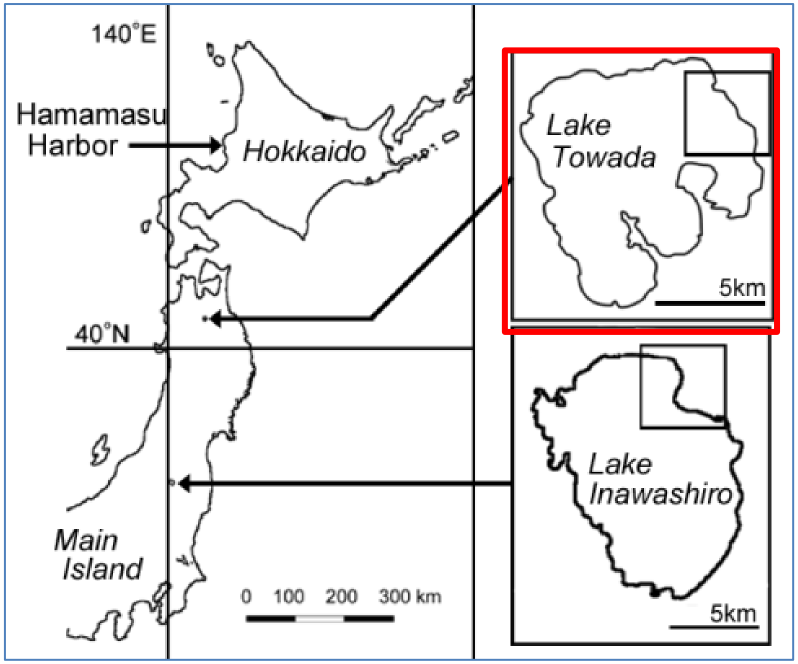


Lake Inawashiro

Spray icing on trees beside lake

Lake Towada has an area of 60 km^2 and an average depth of 70 m.

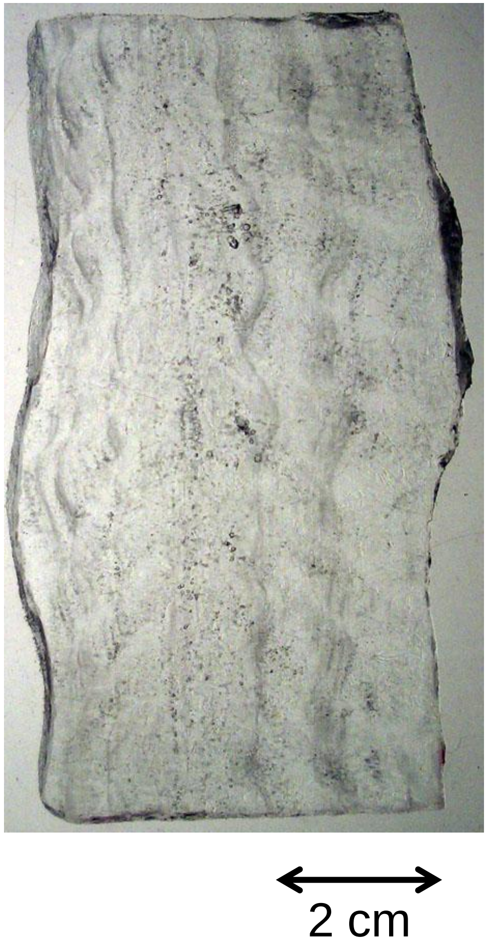
Because of the depth of both lakes, almost the entire water surface is ice free when spray ice usually formed along the shore.

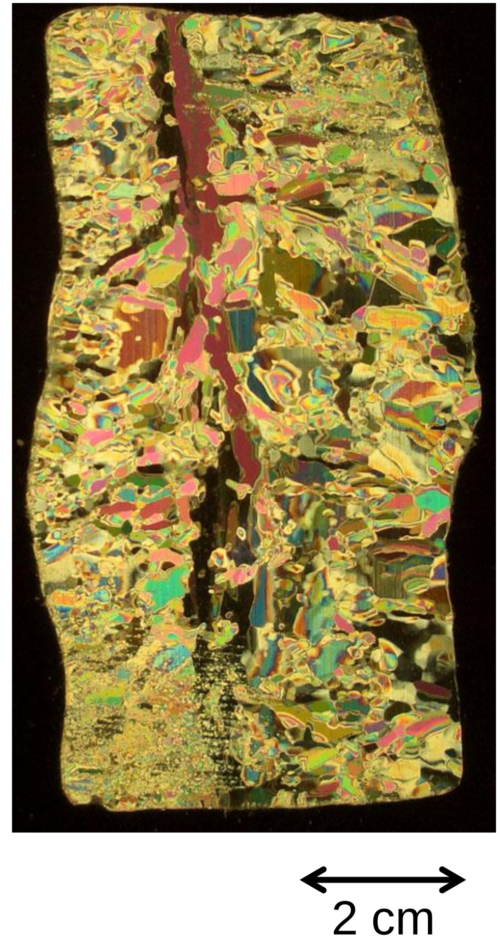


Lake Towada

The samples of spray ice were collected on the east side of the lakes.

- Salinity 0 psu





Thin section

(Photo by Dr. Kawamura)

But there is no drainage channel in the ice.

Oxygen isotopic composition $\delta^{18}O$

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Generally, the concentration of the heavy stable isotope ^{18}O varies with phase changes, and depends on the temperature of the phase changes.

$$\delta^{18}O = \frac{R - R_{SMOW}}{R_{SMOW}} \times 1000 \quad [‰]$$

R: isotopic ratio $H_2{}^{18}O / H_2{}^{16}O$ in the sample

R_{SMOW}: isotopic ratio in Standard Mean Ocean Water.

The snow mass fraction f_s of the spray ice samples is calculated from the isotopic mass balance. (*Sea-ice study*)

Estimation of the contribution or fraction of snow in sea ice, where the snow ice consists of a mixture of snow and sea-water.

$$\delta i = (1 - f_s) \times (\delta w + f) + f_s \times \delta s$$

δi : $\delta^{18}O$ in an ice segment, δw : $\delta^{18}O$ sea-water, δs : $\delta^{18}O$ of snow.

f : an effective fractionation coefficient associated with the freezing of sea-water.

Observational results

Sample	Ice type	$\delta^{18}O$ (‰)
Event 1		
1A-1	Average	1.38
1A-2	Average	0.83
1A-3	Ice	1.09
1A-4	Granular	1.16
1B-1	Ice/Granular	0.42
1B-2	Ice	-0.24
1B-3	Granular	-0.09
1C-1	Ice/Granular	1.15
1C-2	Ice	1.13
1C-3	Granular	1.22
1D	Average	0.26
Event 2		
2A	Ice/Granular	–0.55
2B	Granular	–0.75
2C	Granular	–3.53
Snow		–10.80
Sea water		–0.11

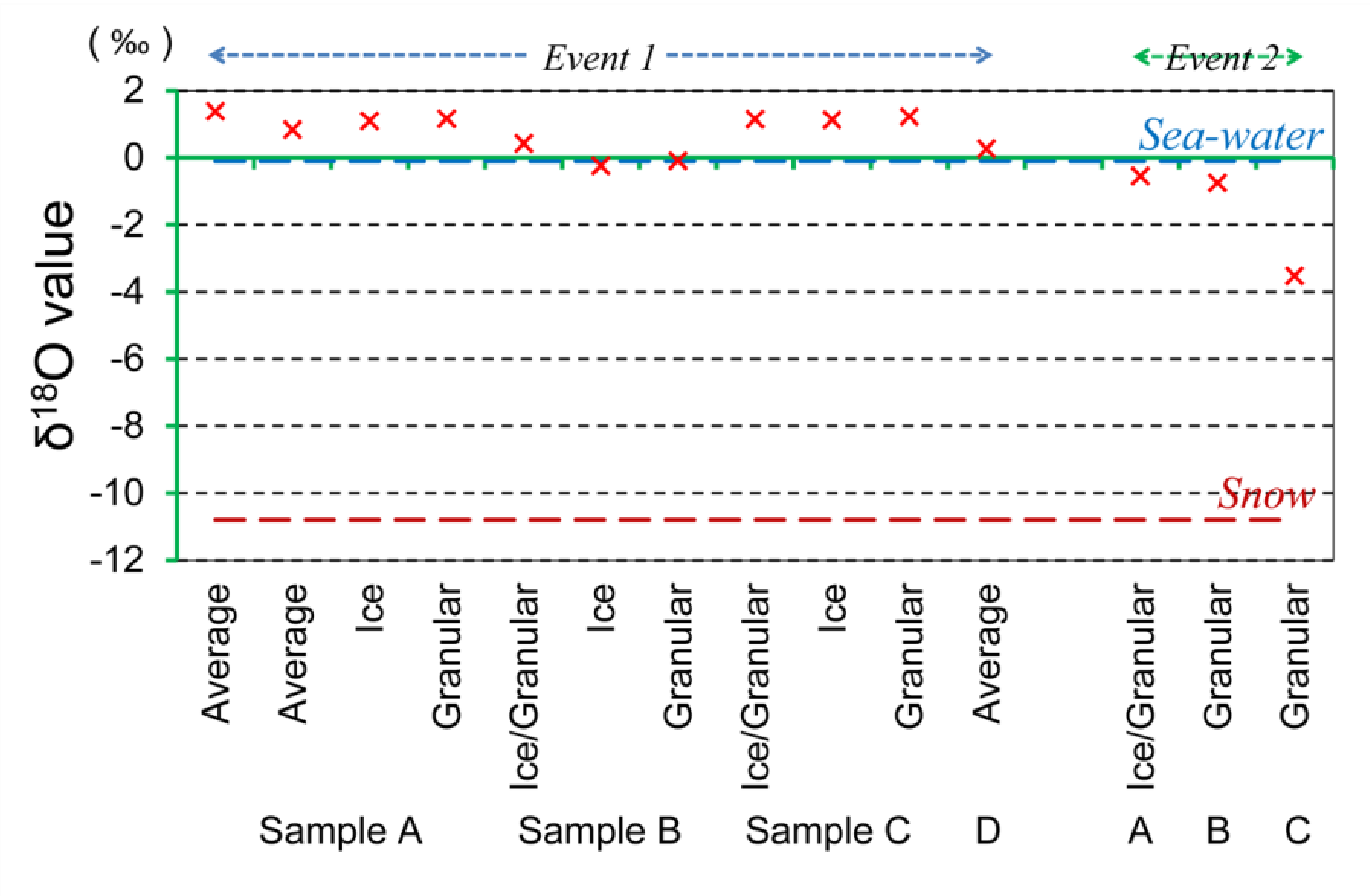
Sample	Ice type	$\delta^{18}O$ (‰)
Lake Inawashiro		
Spray ice	Average	–8.2
Snow		–9.6
Lake water		–9.6
Lake Towada		
Spray ice	Average	–6.8
Snow		–12.5
Lake water		–8.1

← $\delta^{18}O$ value

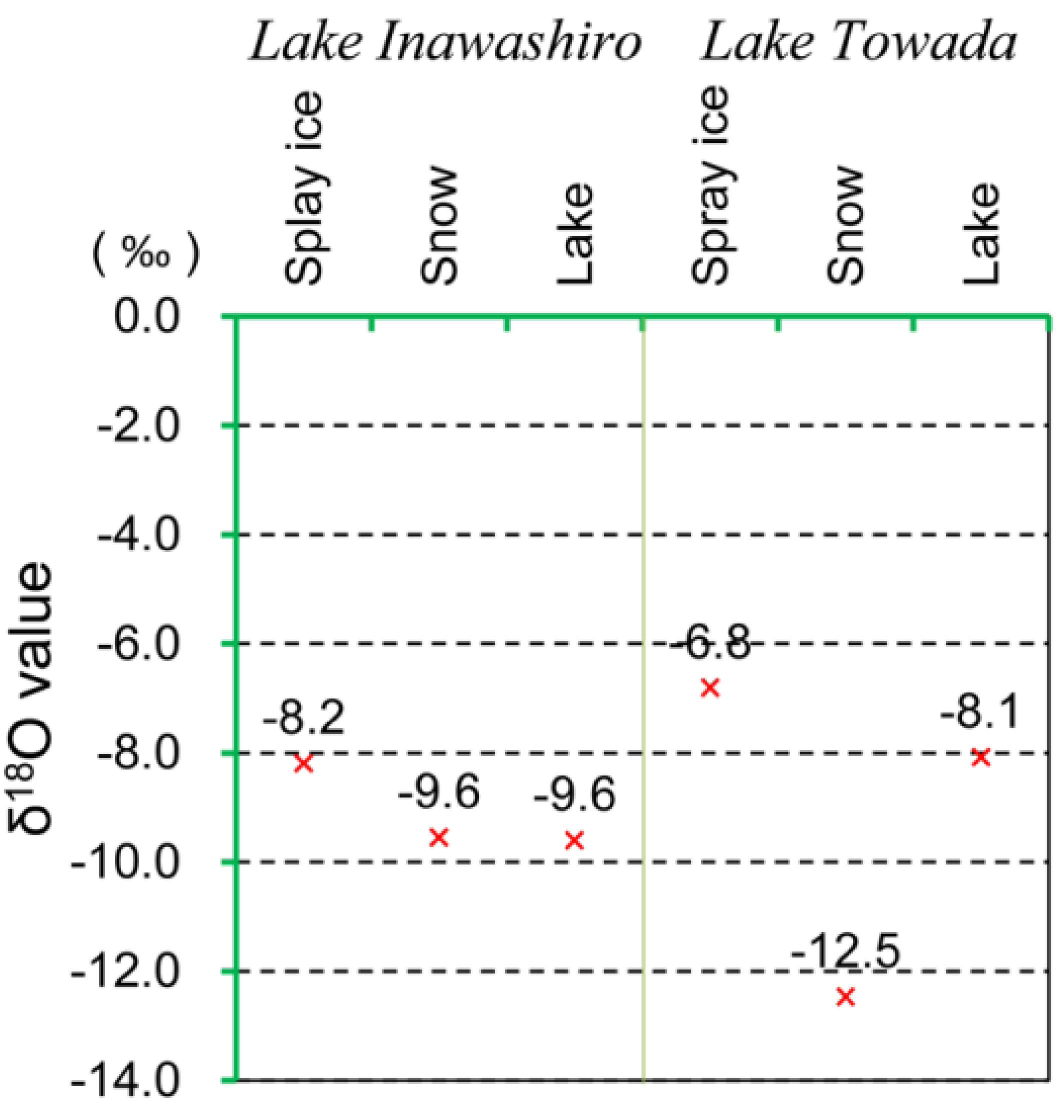
Snow: -10.80 ‰

Sea-water: -0.11 ‰.

Sea water spray icing



Lake-water spray icing



Almost all oxygen isotopic composition values of spray ice are higher than the values of the sea- or lake-water supply.
Isotope fractionation has occurred during the wet growth of the spray ice.
effective fractionation coefficient

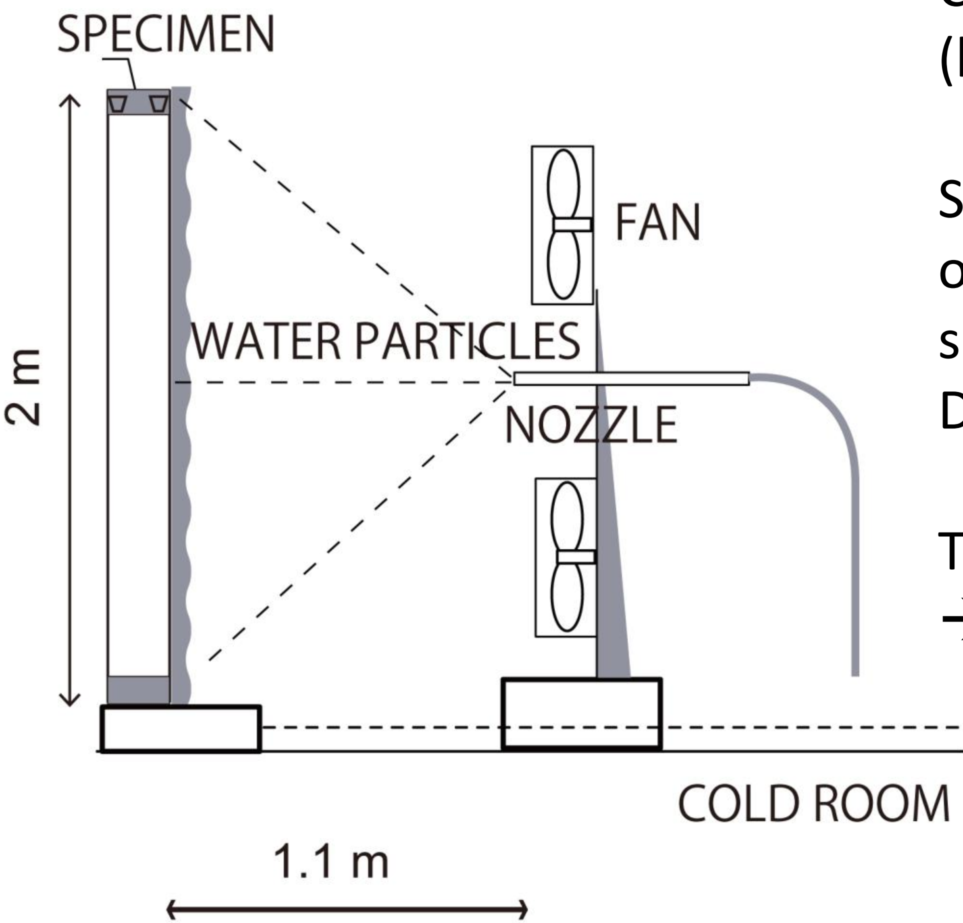
$$\delta i = (1 - f_s) \times (\delta w + \boldsymbol{f}) + f_s \times \delta s$$

in sea ice study

The fractionation coefficient of sea ice, i.e. $f = 3.0$, is over-estimated, since this value decreases with an increment in the growth rate.

To verify the f value, we investigated the isotope fractionation during the wet growth of spray ice through laboratory experiments.

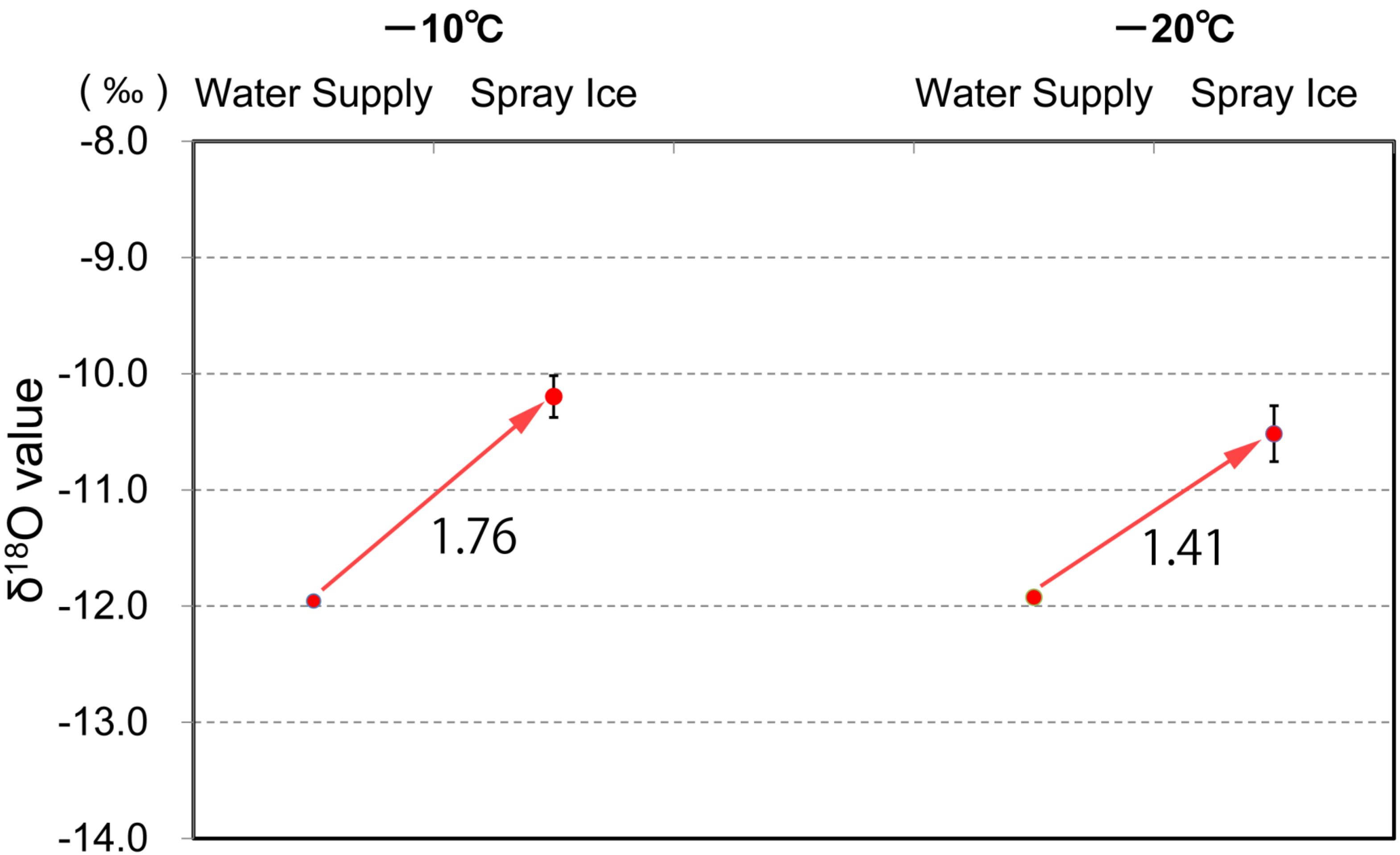
Apparatus



Cylinder
(height: 2 m; diameter: 0.3 m)

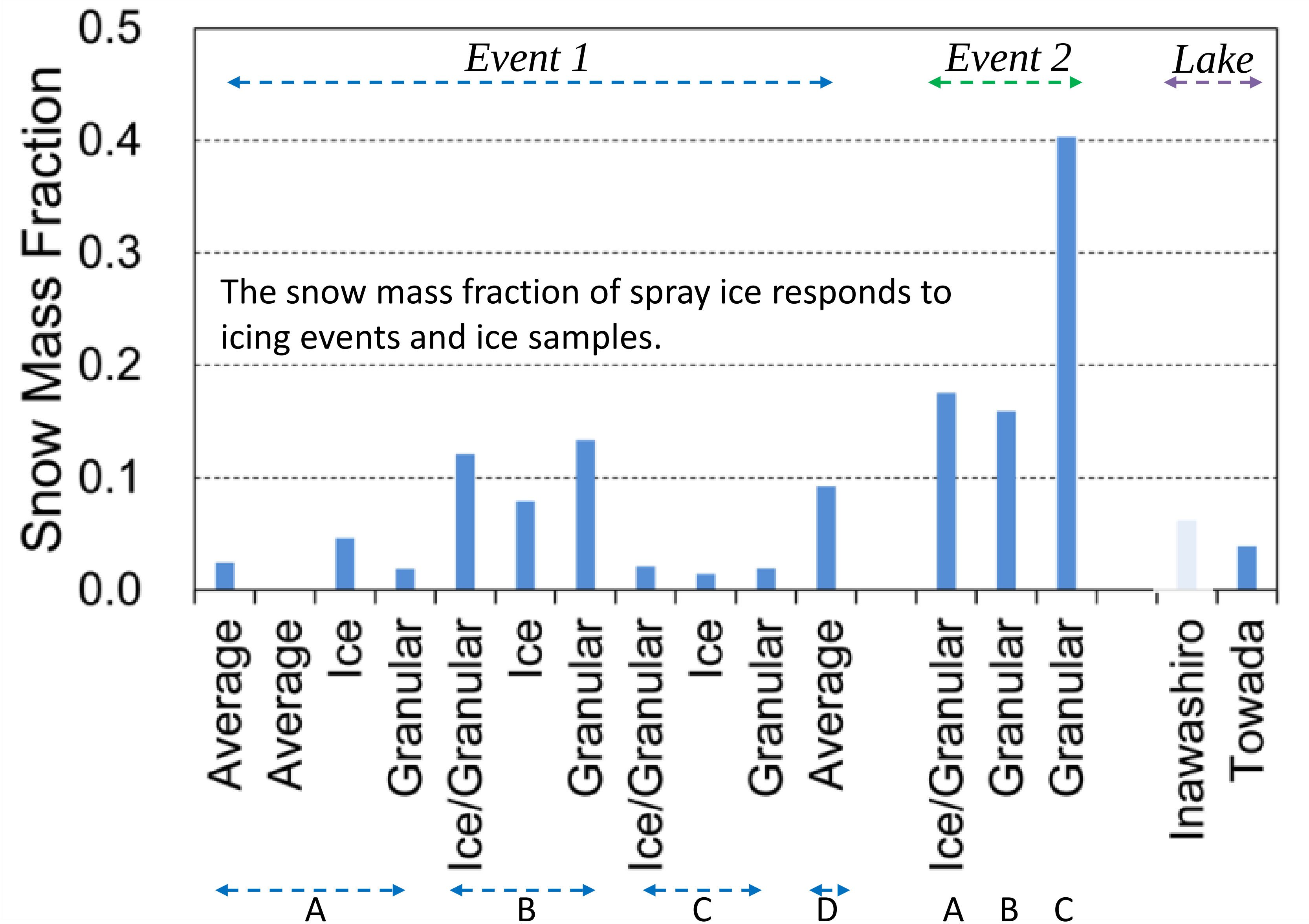
Small water droplets with a diameter of approximately 0.3-0.5 mm were supplied by a fan-shaped spray nozzle.
Distance: 1.1 m

The air temperature: -20 °C. -10 °C.
→Different growth rate



The fractionation coefficient of -10 °C experiments is higher than The fractionation coefficient of the -20 °C experiments. In nature, air temp., wind speed, and growth rate of the spray ice fluctuates from hour to hour, therefore the effective fractionation coefficient is not settled.

<u>f = 1.5 for the calculation of the snow mass fraction.</u>



High snow fractions in the samples demonstrate that snow contributed significantly to the growth of spray ice.

Conclusions

The contribution of snow to spray icing was investigated.

- The spray ice consists of two ice types with different crystal structures: granular ice with uniform, rounded smaller grains and columnar ice.
- The $\delta^{18}O$ values of spray ice are higher than the values of the sea or lake water supply. This difference suggests that isotope fractionation has occurred during the wet growth of spray ice.→ Wet growth of artificial spray ice produced in cold room experiments.
- The $\delta^{18}O$ of the artificial spray ice indicates that the $\delta^{18}O$ values of the spray ice is higher than the value of the water supply. We suggest an effective fractionation coefficient of 1.5 for the spray ice event.
- The snow mass fraction of the spray ice samples is calculated from the isotopic mass balance. The snow mass fraction of spray ice responds to icing events and ice samples.
- The values of granular ice layers tend to be higher than for the other layers, suggesting the contribution of snow accumulation.

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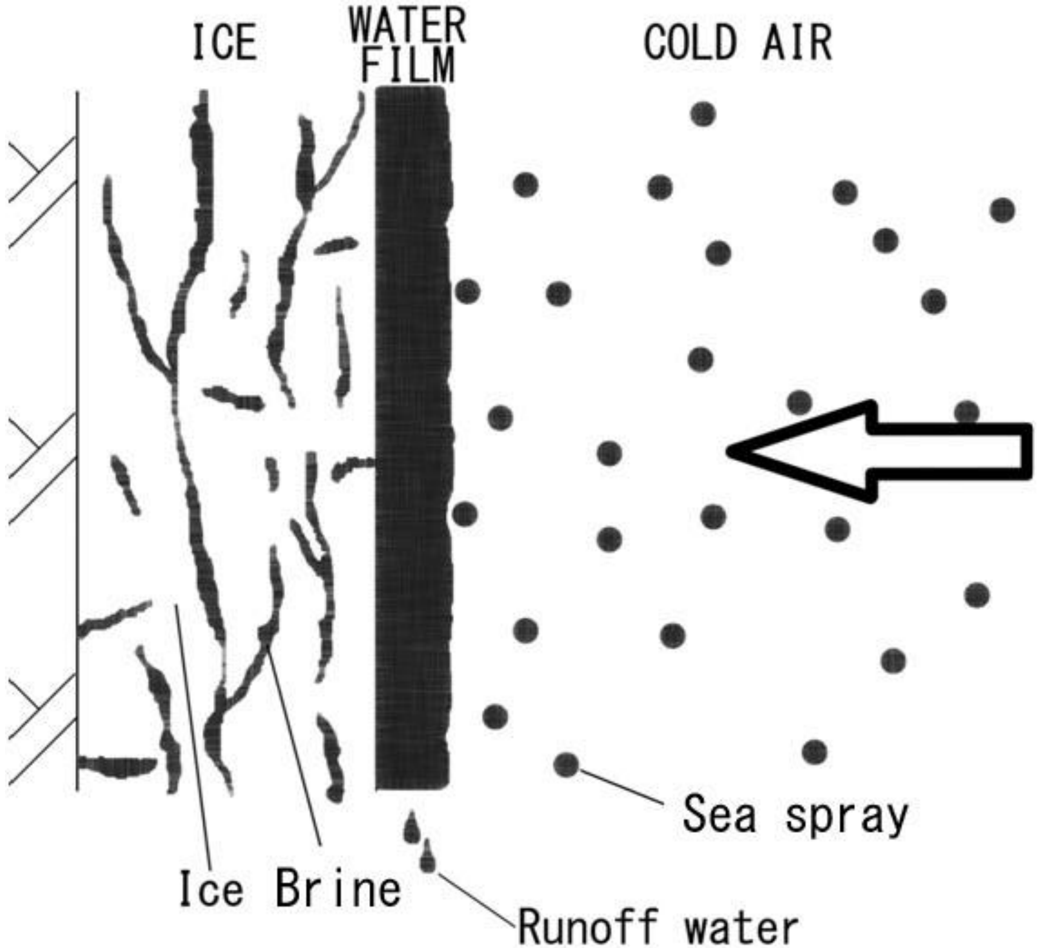
Thank you

Wet growth of sea spray icing



- Brine drainage channel