5 CONCLUSIONS

The multitude of unstable phonons in ice XI under compression, each one leading to a different metastable structure, may interpreted using AIM by the appearance of O—O interactions, since they are markers of structural instability, as bondpaths switch easily between such bonding interactions. The $\mathbf{e}_2$ eigenvectors provide a novel tool for predicting structural change, though they may be most successful when they are sued to describe the rearrangement of hydrogen atoms due its extreme lightness. The findings of this work are consistent with the conclusions of previous work[1], namely that a more drastic molecular reorientation is required to produce an anti-ferroelectric ice VIII structure, which must involve a higher energy barrier. This we demonstrate by showing that the ice VIII-like structure is much more unstable than ice VIII, since the values of the BCP ellipticities of the O—O interactions are much higher in the former, as can be seen from Table 1. Further work underway is to understand how the O—O bonding interactions are related to soft phonon modes by using a supercell approach[3] and to develop a theory of pressure amorphisation through, for example, displacive disorder as inspired by the work of Morrel Cohen[18].

Acknowledgments

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WATER-VAPOR TRANSPORT IN SNOW WITH HIGH TEMPERATURE GRADIENT

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1 INTRODUCTION

Snow crystals change their shapes and states of bonding to each other, after depositing and accumulating on the ground. There have been many basic research studies of snow metamorphism because the dynamic and thermal properties change drastically through it. Water vapor transport in the snow is the cause of dry snow metamorphism, like an isothermal process and temperature gradient process.[1,2]

Depth hoar grows under a temperature gradient. There have been much research about depth hoar since it can be a major factor in avalanche initiation. It was reported that the growth rate of depth hoar snow was proportional to the temperature gradient and the crystal size was a decreasing function of initial density.[3,4,5,6] Those researches were about depth hoar in the temperate region and the effect of the temperature gradient was considered important. Depth hoar snow also exists widely in the Arctic region during winter period.[7] Such Arctic region snow is important as a cold source, when the heat balance of the climate is considered. From observations in Arctic regions such as in Alaska, or Finland, during the severe winter, the lowest temperature is about -40 °C and depth hoar forms under a large temperature gradient even at these low temperatures.[8,9,10]

It was reported that depth hoar crystals developed mostly near the ground although temperature gradient near the ground was smaller than near the surface layer.[8,11] Such tendency was inconsistent with previous reports and was thought to be due to the difference in growth conditions. It was reported that depth hoar in the Arctic region was affected firstly by temperature and secondarily by temperature gradient due to water vapor concentration.[12] Sturm and Benson (1997) were pioneers, who studied the relationship between water vapor transport and depth hoar development in the subarctic snow with field experiment.[11] Our previous study also presents the possibility that water vapor transfer affected density change, snow temperature distribution, and crystal growth.[13] However, sufficient experimental confirmation of mass transfer have not occurred.

In this study, to clarify the effect of water vapor, we chose a wide temperature range (-65 °C to -12 °C), for which the water vapor concentrations differed by a factor 1000 between the lowest and highest temperatures, and carried out snow metamorphism experiment under high temperature gradient in a cold room. The density change with water vapor was measured and the effects of water vapor transport on crystal growth, and on density change were examined experimentally.

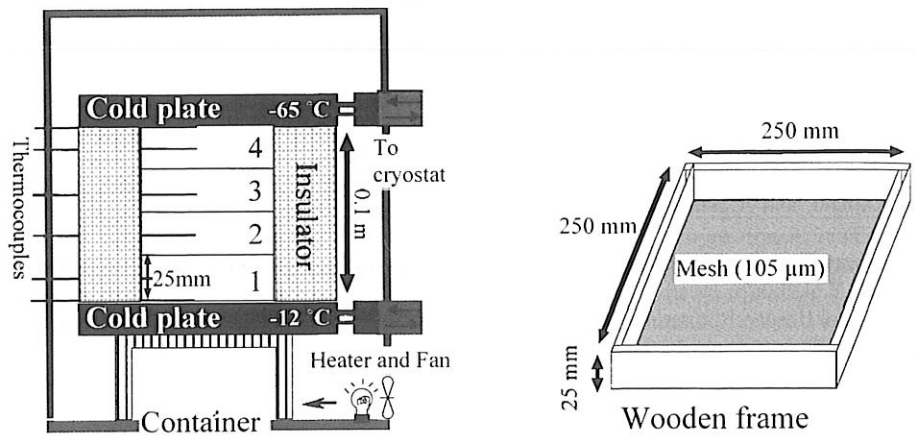

Figure 1 *Schematic experimental equipment and wooden frame affixed nylon mesh.*

2 EXPERIMENTAL

Figure 1 presents schematic of the experimental equipment. A constant-temperature container (0.6×0.7×1.2 m) was installed in a -15 °C cold room. The inside temperature was maintained at -10±1 °C by heater and fan connected to a thermo regulator. A sample box was made of 0.1 m thickness insulator, blocking heat from the outside. In order to measure the change of mass due to water vapor transfer, wooden frames affixed with a nylon mesh were used; the frame size was 250×250×25 mm, the frame thickness was 10 mm and the mesh opening is 105 μm. The nylon mesh can be penetrated by water vapor, but it prevents the transfer of snow particles. The frames were superimposed in four layers, in order from the bottom, layer 1, layer 2, layer 3, and layer 4. The snow sample was sieved in the frame and then installed in the sample box. We used lightly compacted snow (Class 2dc) for the initial stage; the calculated average diameter was 2.7×10^{-4} m, and the density was 165 kg m^{-3} (Figure 2(a)).[11] The top and bottom ends of the box were fully covered with cold plates, to prevent inflow of water vapor from the outside and then the box was installed in the container. The plates were connected to a circulating cryostat, so that temperatures can be individually controlled. Copper-Constantan thermocouples were installed at the positions 0, 12.5, 37.5, 62.5, 87.5, and 100 mm from the bottom. The thermocouple has been connected to a digital multimeter using zero-temperature standard. The temperatures were recorded at one-minute intervals.

The snow sample was kept at -10 °C as an initial state. Next, the cooling plate was set at a fixed temperature (bottom end: -12 °C, top end: -65 °C). Therefore, the snow sample was subjected to a 530 K m^{-1} temperature gradient condition for 133 hours.

3 ANALYSIS

Crystal shapes of each layer were observed and classified into three types: the initial crystal type (lightly compacted snow (Class 2dc)), solid type depth hoar (Class 3mx, 4a) and skeleton type depth hoar (Class 5cp).[14] Snow crystal photomicrographs of each layer were taken and then the projected area of the crystals were obtained.

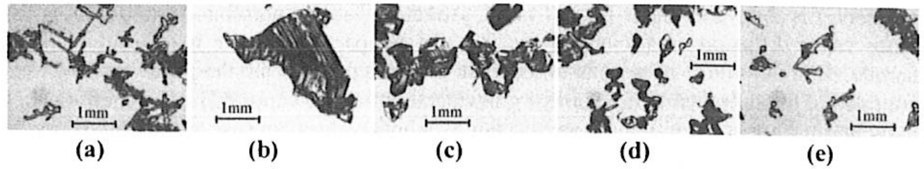

Figure 2 *Photograph of snow crystal at initial and final stage of this experiment. (a) initial snow: lightly compacted snow (Class 2dc), (b) layer 1: skeleton type depth hoar (Class 5cp), (c) layer 2: solid and skeleton type depth hoar (Class 3mx, 4a, 5cp), (d) layer 3: solid type depth hoar (Class 3mx, 4a), (e) layer 4: lightly compacted snow (Class 2dc).*

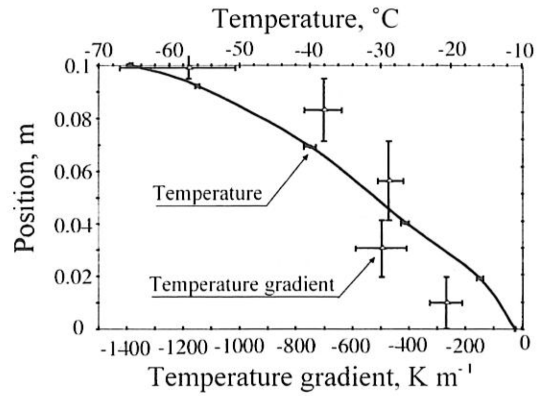

Figure 3 *Quasi-steady state temperature distribution and calculated temperature gradient. Solid circles are measured temperature and are connected by smooth solid line. Open triangle is calculated temperature gradient.*

The circle diameter equivalent to the projected area was calculated. Such diameter of the initial snow crystal was also calculated using the same method. We calculated 250 ~ 400 crystals in each layer. In this paper, we use the statistically averaged diameter and the growth rate, which is the amount of change in the diameter per unit time.

The density change of each layer was measured in the following method. First, we measured the weight of each wooden frame. Second, initial snow was sieved and initial mass of each layer was weighed. Third, after the experiment, we confirmed there were no voids between the layers and mass of each layer was weighed. The density of each layer was calculated from the volume and mass of the sample.

The mass difference between layers was divided by the cross-sectional area of the snow sample and the duration of the experiment, and the measured water vapor flux f_m was obtained. The measured mass flux M_m was calculated from the density change divided by the duration of the experiment.

The calculated water vapor flux f_c was calculated from the quasi-steady state temperature distribution in the snow sample. Fick's law was used to model the vapor flux. The calculation was performed as follows:

$$f = \partial D_e \frac{\partial C}{\partial T}\frac{\partial T}{\partial z} = \partial D_e \frac{\partial C}{\partial z} \quad (1)$$

Here, f is the water vapor flux, C is the saturated water vapor concentration, D_e is the water vapor diffusion coefficient in air, T is the temperature, and z is a position in the sample. In this study, it was assumed that the water vapor in the snow sample was saturated. Although there were some arguments about water vapor diffusion coefficient in snow and tortuosity dependence, we did not use those values because we have no data on how those values change during dry snow metamorphism.[15, 16] In reality, we think those values probably affect the water vapor flux.

The saturated water vapor concentration C was calculated from the temperature at each position. The distribution of the water vapor flux was then calculated using the water vapor diffusion coefficient D_e. Finally, we compared f_c and f_m and examined the relationship between the water vapor flux and the crystal growth rate.

It is possible to require a change of mass per unit volume and unit time, by differentiating equation (1), that is, the calculated mass flux M_c at position z.

$$\frac{d\partial}{dt} = \frac{df}{dz} = \partial D_e \frac{\partial^2 C}{\partial z^2} \qquad (2)$$

Here, ρ is density of each layer, and t is time. M_c and M_m were compared and the relationship between the density change and the mass flux were examined.

4 RESULTS AND DISCUSSION

4.1 Snow type and temperature distribution

The snow type of each layer after metamorphism is given in Figure 2. Layer 4 consisted entirely of lightly compacted snow (Class 2dc) that had not changed from its initial stage. It changed to solid (Class 3mx, 4a) and skeleton type (Class 5cp) depth hoar snow in layers 3, 2, and 1. Especially, layer 1 had many greatly developed skeleton type (Class 5cp) depth hoar snow crystals and was very fragile.

Next, the distribution of temperature and temperature gradient of the quasi steady state is depicted in Figure 3. The snow sample was initially kept at -10 °C, and was cooled from the top cooling plate to -65 °C, reaching a quasi steady state in about 6 hours. The temperature distribution showed upward convex curve. Therefore, the temperature gradient was not uniform in the sample. This tendency is same as a typical temperature profile in subarctic snow.[11] In addition, the nonlinearity of the snow temperature distribution resulted from water vapor transport in the snow.[17]

The results of the crystal growth rate in each layer, along with the temperature and the magnitude of the temperature gradient, are listed in Table 1. The growth rate is not always proportional to the temperature gradient. Layers with a higher mean temperature yielded larger particles, as has been reported for subarctic snow.[8, 11, 12]

Table 1 *Temperature, temperature gradient, and growth rate of each layer. Temperature was measured value in the layer. Temperature gradient was inside value of each layer. Growth rate was averaged value of each layer.*

layer	*Temperatue* (°C)	*Temperature gradient* (K m^{-1})	*Growth rate* (x10^{-10} m s^{-1})
1	-16	-270	10.3
2	-26	-500	4.9
3	-40	-480	0.8
4	-56	-700	-0.5

4.2 Water vapor flux and growth rate

Water vapor transport develops depth hoar crystals. It has been reported that the growth rate agrees well with the calculated water vapor flux.[12] Figure 4 shows the relationship between the water vapor fluxes (f_m and f_c) and the growth rate of each layer. The distribution of the water vapor fluxes and the growth rate agreed well. f_m and f_c also agreed well. This indicates the validity of f_c and the temperature distribution in the snow largely reflected crystal growth.

Figure 5 re-expresses the relationship between f_c and the growth rate seen in Figure 4. It was demonstrated that depth hoar crystals could not grow very large in a layer with low water vapor flux, even if the temperature gradient is large. We can see this tendency when the temperature is very low. In the figure, it also accounts for the result at 290 kg m^{-3} which was obtained under conditions similar to those reported in Kamata et al. (1999).[12] A high proportion coefficient was required when the initial density was low. In short, depth hoar crystal was able to grow extensively when the initial density was low, since spaces in the snow were large. This agreed with previous studies, in which depth hoar snow developed when the initial density was low.[3, 5, 6]

In this study, the range of water vapor flux was from 0.3 to 8 $\times 10^{-7}$ kg m^{-2} s^{-1}. Sturm and Benson (1997) observed temperature profiles in snow and calculated layer-to-layer vapor flux using Fick's law.[11] They obtained an average water vapor flux about 2.5 $\times 10^{-7}$ kg m^{-2} s^{-1}, with peak values at 15 $\times 10^{-7}$ kg m^{-2} s^{-1}. Our results fell within their value range with the exception of the extremely low temperature layer (less than about -40 °C).

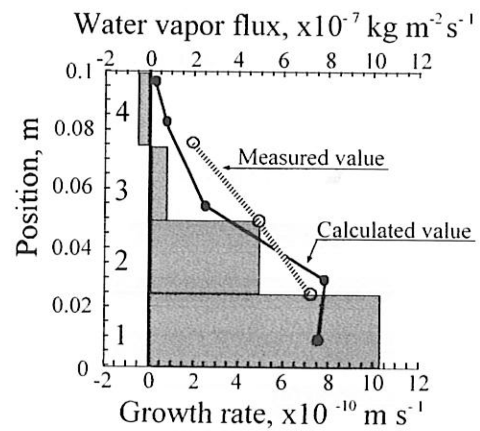

Figure 4 *Relationship between the water vapor fluxes and the crystal growth rate in each layer. Solid circle is the calculated water vapor flux. Open circle is the measured water vapor flux. Columns are the average growth rate of each layer.*

4.3 Mass flux and density change

The water vapor flux seems to affect significantly the growth rate of depth hoar snow. It seemed that water vapor transportation also caused a density change in snow. The initial and final density of each layer is illustrated in Figure 6. Before and after the experiment, the lost mass was only 0.5 %. The density of layer 1 (warmest) decreased,

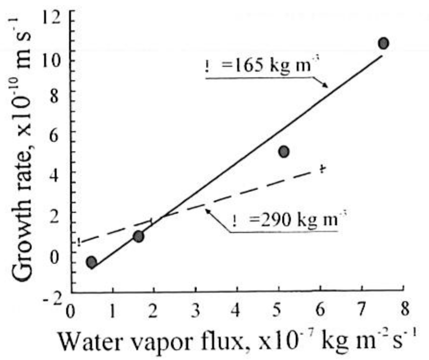

Figure 5 *Re-expressed relationships between the water vapor flux and the growth rate seen in Figure 4. Previous result reported in Kamata et al. (1999) was also shown to examine the density dependence.*

while the densities of layers 2, 3, and 4 increased. We calculated the density change subtracting initial density from final one. Figure 7 shows the relationship between the mass fluxes (M_m and M_c) and the density change. M_m and M_c were of the same order, and the distribution of both mass fluxes showed the same tendency as the density change. In the layer 1, M_c showed a negative value where the density decreased. This result shows that it might be possible to estimate the amount of density change from the temperature distribution within the snow.

An average mass flux reported in Sturm and Benson (1997) was about 50 $\times 10^{-7}$ kg m^{-3} s^{-1}, with peak values at 500 $\times 10^{-7}$ kg m^{-3} s^{-1}.[11] The range of our mass fluxes was within their values.

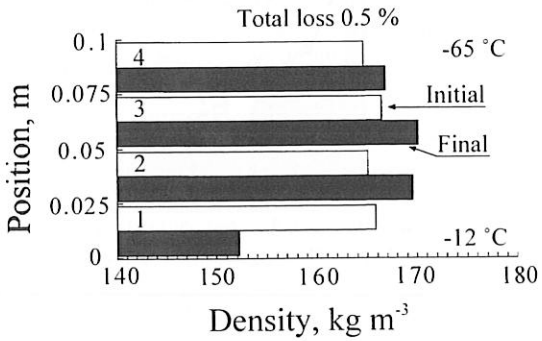

Figure 6 *Density change over the duration of the test. Blank columns show initial density of each layer. Black columns show final density of each layer.*

4.4 Snow metamorphism under high temperature gradient

Water vapor transport in snow not only greatly affected the crystal growth, but also caused density change. We tried to examine depth hoar growth for a wide range of temperature and temperature gradient from the viewpoint of water vapor flux (Figure 8). The isogram line of water vapor flux was ideally obtained using equation (1) in the following way. The value of water vapor flux was fixed and then temperature gradient was calculated at certain temperature value. We connected those values on the graph.

The hatched area is the region where observations and experiments of previous studies on depth hoar snow have been carried out. This area is sensitive to the temperature gradient even if the temperature gradient changes only slightly, since the isogram line indicates that the water vapor flux changes significantly. This accounts for previous studies reporting that the growth rate of depth hoar is proportional to the magnitude of the temperature gradient.[3,4,5,6] In contrast, the experiment in this study was carried out in the circled region. The isogram line stands in this region. Therefore, the amount of change in the water vapor flux is slight even if the temperature gradient changes significantly. However, the water vapor flux changes greatly, when the temperature changes. In this way, by analyzing the water vapor flux distribution, we could understand temperature gradient metamorphism over a wide temperature range.

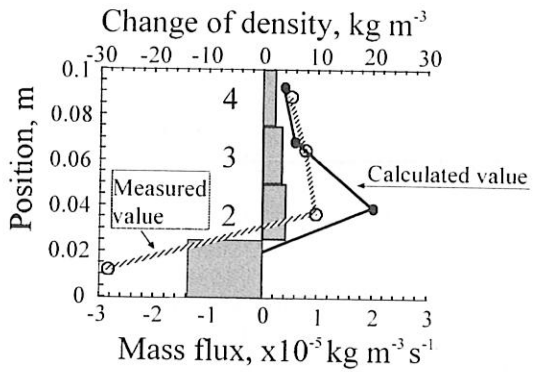

Figure 7 *Relationship between density change and mass flux. Solid circle is the calculated water vapor flux. Open circle is the measured water vapor flux. Columns are the density change of each layer.*

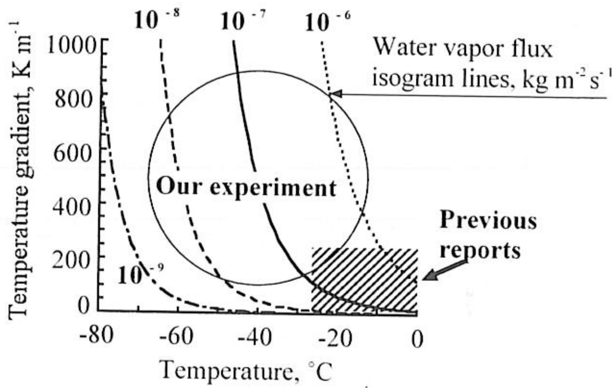

Figure 8 *Water vapor isogram line on temperature and temperature gradient graph. Isogram lines were ideally calculated using formula (1). Hatched area is sensitive to temperature gradient. Large circle area is sensitive to temperature.*

5 CONCLUSIONS

Using equipment that can measure water vapor transfer, to examine the effect of water vapor transport on growth rate of grains and on density changes over a wide range of temperatures and temperature gradients, an experiment under high temperature gradient was carried out. The growth rate of depth hoar snow was found to be proportional to the water vapor flux. The measured water vapor flux and the water vapor flux calculated from the temperature distribution agreed well. In addition, the calculated mass flux and the measured mass flux also agreed well. These results helped us understand the relationship between temperature gradient metamorphism and water vapor flux over a wide temperature range. In the future, the experiments would be carried out under various conditions exactly, and these kinds of data might be accumulated.

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EXPERIMENTAL GEOSCIENCE IN A FREEZER: ICE AND ICY COMPOUNDS AS USEFUL EDUCATIONAL ANALOGUES FOR TEACHING EARTH AND PLANETARY MATERIALS SCIENCE AND THE PHYSICAL SCIENCES

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1 INTRODUCTION AND BACKGROUND

As our societies become ever more technologically complex, citizens and decision makers need to become more knowledgeable about the science of materials if they are not to become victims of technology rather than the masters of it. Many recent examples of failures of public-works projects, such as collapses of airport terminals, tunnels, and aircraft losses, have issues regarding materials selection and properties. Decision makers have learned that they cannot passively accept expert opinion and need to be knowledgeable enough to ask the right questions concerning complex public-works, transportation and other large and costly projects. Moreover, many science students and professionals generally have but a rudimentary knowledge of the science of materials and hence are often unprepared for research involving knowledge of material properties and processes.

The purpose of this paper is to stimulate interactive discussion on how to exploit what we have learned about the physics and chemistry of ice in the PCI community by developing engaging, inexpensive, and safe laboratory experiments on ices for use in classrooms at the primary school to lower-division undergraduate university level. The behavior of terrestrial glacial ice (plastic flow, brittle behavior, development of crystallographic preferred orientations and property anisotropy, etc.) has long been recognized by our community as instructive to students of Earth's interior and the icy planets and moons and the physical sciences in general. Education for students is most effective when it uses a balance of classroom instruction, personal reading, and "hands on" laboratory experience in working with real materials. This process of doing science rather than just reading about it is often called "active learning" and experience has shown that it is an effective tool in demonstrating scientific principles and also showing how science is actually done. In the geosciences, lab experience of beginning students is usually limited to field trips and classroom identification of rocks and minerals. What is typically lacking is lab experience using experiments on mineral systems in which the fundamental material properties and governing processes are investigated. To do such experiments on silicate mineral systems, particularly at the high-school or undergraduate level, is often impractical, given the high-temperatures required to investigate thermally-activated processes and melting and the high pressures that are often necessary to investigate metamorphic reactions.

Thus not only do ice and icy compounds occur on Earth, in polar planetary regions,