

## THE QUANTITATIVE GROWTH LAW OF ICE CRYSTALS AND ITS NEW MODEL

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**Abstract.** An improved new wedge-shaped chamber of ice thermal diffusion was used to obtain a more complete and overall growing law of ice crystals. The chamber has stable environmental conditions and can measure three dimension sizes of ice crystal easy. The experiment was done under different ice supersaturation (from 0% to 25%), different temperature (from 0°C to -30°C) and longer periods of the time (50 minutes or more).

The wedge-shaped chamber of ice thermal diffusion includes the wedge-shaped chamber, an ice crystal sliding mechanism, microphotographic system, temperature measuring system, computer system, etc.

According to our more than 4,000 data, a quantitative, more complete and overall growing result of an ice crystal in the above ice supersaturation and temperature field had been presented. A new method for quantitative indicating the form of different kinds of ice crystals has been suggested. We can use  $2a/c$  to decide seven kinds of ice crystals, i.e. dendrite, very thin plate, thin plate, thick plate, prism, long prism and needle.

On the basis of a great number of our experimental data, several new characteristics of ice-crystal growth in the Wulff growth region and the region of abrupt change of crystal forms were found. We studied the growth rates of ice crystal at different temperature and ice supersaturation. The author points out that  $d(2a)/dt$  and  $dc/dt$  plotted as a function of temperature at  $(S_i - 1) = 1, 3, 6, 9, 12, 15$  and 18%; their changes with time; and their characteristics at water saturation etc.

In the region below the water saturation line, when  $(S_i - 1)$  is less than 6%, prisms and thick plates predominate, which is consistent with Wulff's prism growth theory in most of the region. When  $(S_i - 1) = 6-8\%$ , there is a region of sudden change in crystal forms, where the forms are mainly determined by temperature e.g. very thin plates at -15°C, long prisms around -25°C, etc.

In the field of temperature and ice supersaturation when stable growth of the ice crystal is reached, a minimum and maximum may exist for

$(S_i - 1) \geq 6-8\%$ , the former at about  $-5^\circ\text{C}$  of ice needles and the latter around  $-15^\circ\text{C}$  of very thin plates (below water saturation) or of dendrites and spatial plates (above water saturation). As the temperature is decreased from  $-5^\circ\text{C}$  to  $-15^\circ\text{C}$ , the ice crystal forms experience a transition in the sequence of long prisms, prisms, thick plates, thin plates, to the above-mentioned forms for the maximum respectively. As the temperature drops further, the various crystal forms appear in a reverse order until long prisms prevail near  $-25^\circ\text{C}$  with the absence of ice needles (see Fig. 1).

In this paper, the characteristics of ice crystal growth in low ice supersaturation region, the quantitative comparison of static and dynamic experiments for ice crystal growth, and the comparison between our new work and former's works etc. have been presented.

Lastly, the author gives new models of ice crystal growth law in temperature-ice supersaturation or vapor density excess field which were built on the above bases. The inadequacy and thus a necessity for improvement of the Kobayashi-Pruppacher model are discussed here.

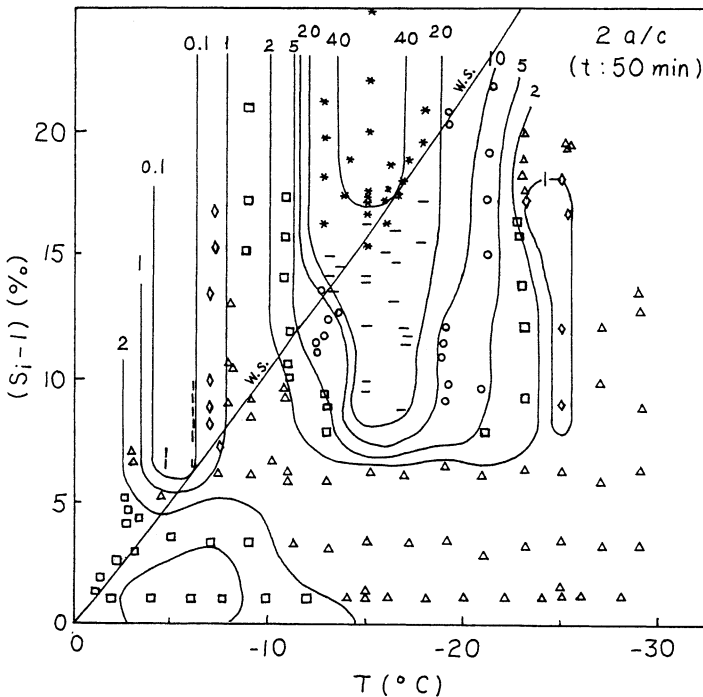


FIG. 1. Ice crystal form variation determined in temperature—ice supersaturation field (time=50 minutes).

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## DISCUSSION

Kobayashi [18-1]

1. You insisted your diagram is new and quantitative. But I cannot find any essential difference between yours and ours, which I mean Nakaya, Hallett and Mason and Kobayashis', except the crystal forms at low supersaturation.

What my diagram insists is very simple but quite important, that is, variation of snow crystal form can be explained by both changes of crystal habit and morphological instability of growing faces. Habit varies with temperature and morphological instability depends on supersaturation.

My diagram has been generally accepted for more than twenty years by many snow crystal people and recently Kuroda and Lackmann gave a beautiful theoretical explanation.

Your data at the region of low supersaturation contradict to our data, and if your data were correct, it will bring about another complex problem to understand the variation of snow crystal morphology.

2. I would like to remind you just one point which might produce some error to obtain  $2a/c$  values.

[18-2]

In your experimental set-up, you nucleated small ice crystals in a different chamber and transferred into a growth chamber.

In this procedure, the influence of initial crystal shape may not be neglected to obtain  $2a/c$  value at final stage.

I am not sure 50 min observations are long enough to eliminate such an influence especially at low supersaturation conditions.

A: [18-2]

1. Please see Fig. 8, Fig. 14 in my paper objectively, and compare with

Kobayashi's model (Fig. 10 in my paper) carefully. It is very easy to find that they are different each other as following.

1. Kobayashi's model only had a few data which were not exact between water saturation and ice saturation (please see (8), T. Kobayashi: The growth of snow crystals at low supersaturations. *Phyl. Mag.*, **6**, (1961), 1363–1370); In same region, we have much more data and they are exact.

2. In above region, according to Kobayashi's model, the shape and habit of ice crystals were decided by temperature  $T$  and excess vapor density  $\Delta\rho$ ; then it is an inference only. According to our more than 1,000 data (every 5 min., there is a field the same as Fig. 14 in our work), we found that: a. there is the prism region in low ( $S_i-1$ )—low  $T$ ; b. There is a region where the form of ice crystal changes sharply in ( $S_i-1$ )=6–8%. c.  $T$  is very important, then  $\Delta\rho$  is not important to decide form of ice crystal in the above region.

3. Our data are quantitative and exact. We decided the form of ice crystal objectively. We believe Nakaya's, Hallett and Mason's, and Kobayashi's works were very important, and our data are as same as above data in the region where is higher than water saturation only.

Now, 25 years passed, and many new results were obtained, we think that objective results will be decided by the history.

4. We decide the form of ice crystal according to the characteristics of morphology; and  $2a/c$  represents the characteristics of morphology, so we use  $2a/c$  to decide the basic feature of ice crystal.

In our experiments, we measured all sizes of initial ice crystals (or we call ice embryo) when time was  $t=0$  min. The size of all embryo was between 20–30  $\mu\text{m}$ . So when  $t=0$  min, the initial field of  $2a/c$  was near over ( $\approx 1.0$ ). According to our data (Please see Fig. 1, Fig. 2 in my paper), we believe 50 min observation is good enough in low ice supersaturation regions. Of course, if we have the chance, we can do longer observations.