Polar Meteorol. Glaciol., **12**, 79–85, 1998

THE ROLE OF FLOE SIZE IN ICE DYNAMICS

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Abstract: The mechanical characteristics of the ice-covered sea are dictated primarily by the amount of ice found in the area, but several other elements also have influence. The floe size is one such element and is investigated in this article.

Through numerical experiments, the floe size is found to be important in ice dynamics. However, not only the floe size itself but its distribution is critical. A sea with floes of various sizes deforms less than a sea with floes of uniform size under the application of the same force.

Ice covering 30% or less of the total area does not sustain compression, regardless of the floe size and its distribution. A sea with such sparse ice cover is equivalent to an open sea without ice in terms of dynamics.

The process of floe growth through the coagulation of adjacent floes to one another is also explained. Motion is found to be essential for such growth, but the same motion causes reduction of floe size through breaking. Motion is thus an important factor in both increase and decrease of floe size. And, as the floe size largely determines the mechanical characteristics of the ice-covered sea, motion seems to be quite important in ice dynamics.

1. Introduction

The surface of an ice-covered sea contains a mixture of open sea and sea ice. Providing that the physical characteristics of the constituting materials, *i.e.* ice and water, are given, the dynamics of the ice sea is dictated primarily by their ratio. However, the actual ice cover, of concentration, c%, does not contain any point occupied by c% of ice; c% of all the points are occupied by 100% ice and the rest of points by 0% ice. Sea ice dynamics is influenced by the distribution of ice. The distribution of ice within an area is indicated by the shape and size of floes.

In this article the author investigates how sea ice dynamics is influenced by the floe size.

2. A Two-dimensional Sample of Ice-covered Sea

A square shaped sea surface is considered. This area is divided into N^2 square grids. Each grid is filled with either ice or water, *i.e.* local ice concentration is either 100% or 0%. Figure 1 shows one sample of such a model. The model approximates the real ice sea better as the number N increases. Table 1 summarizes the size of grid for various sizes of investigation area and some N values.

In this article the ice is assumed to be elastic with a large elastic coefficient, while

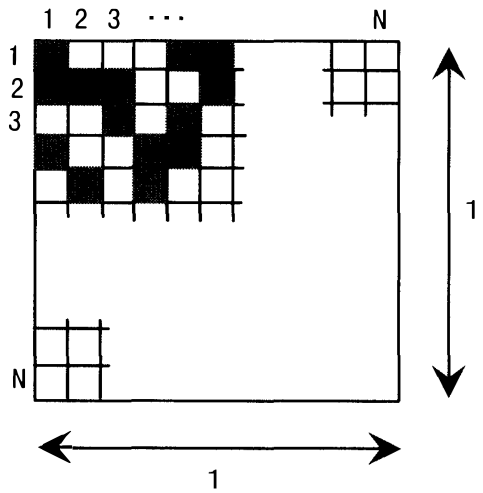

Fig. 1. A sample ice-covered sea.

Table 1. Grid size.

Number of grids \ Size of a square	1	1000 km	100 km	10 km	1 km	100 m
10000	0.01	10 km	1 km	100 m	10 m	1 m
1000000	0.001	1 km	100 m	10 m	1 m	10 cm
100000000	0.0001	100 m	10 m	1 m	10 cm	1 cm

the open water is freely deformable.

3. Compression Test of Ice-covered Sea

3.1. Experiment

An ice-covered sea is believed to sustain compression but no tension, as floes can be moved apart from each other with very little force. The compression-tension asymmetry is one of the distinct characteristics of ice-covered sea, in contrast to the open sea, which behaves in the same manner under both compression and tension. However, an area containing little ice cannot sustain compression either. The behavior becomes symmetrical, and the area, though containing some ice, resembles an open sea rather than an ice-covered sea. Such a sea area should be excluded from the ice-covered sea in the investigation of ice dynamics.

A uni-axial compression test was done numerically to clarify this point. A hypothetical ice-covered sea is placed between a pair of pressing plates. One of the plates moves toward the other one with a specified speed. The pressure at the fixed plate is recorded. Samples with various grid divisions and various ice concentration values are tested.

3.2. Small floes

The first group of experiments assumes that the ice-covered sea consists of equally sized floes. Each grid square containing ice is regarded as a floe of that size. When two floes are in contact with each other, the boundary has no cohesion. The floes can be detached from and slip against to each other under the application of force. The floes resists compression only. An open water grid, *i.e.* the grid without ice in it, does not sustain the compression either, and is freely deformable.

The results are summarized in Fig. 2. The stress is non-dimensional: the stress, a sample consisting of a single piece of solid ice floe (N = 1, concentration = 100%) would show for the given strain, is set to 100. The stress recorded shortly after the start of the experiment is plotted to avoid the strain hardening. Turning of the floe and lateral motion are slight at this early stage, and are neglected.

Virtually no ice sea sustains the compression, unless the concentration is extremely high. This suggests that the assumptions made on the grid boundary may not be realistic.

However, if a huge area is covered by ice, the maximum floe size can be quite small relative to the entire area. And neighboring floes may not be coalesce under certain thermal conditions. This is the state the model describes. For instance, the sea off Antarctica may show no resistance to compression on a large scale under some circumstances.

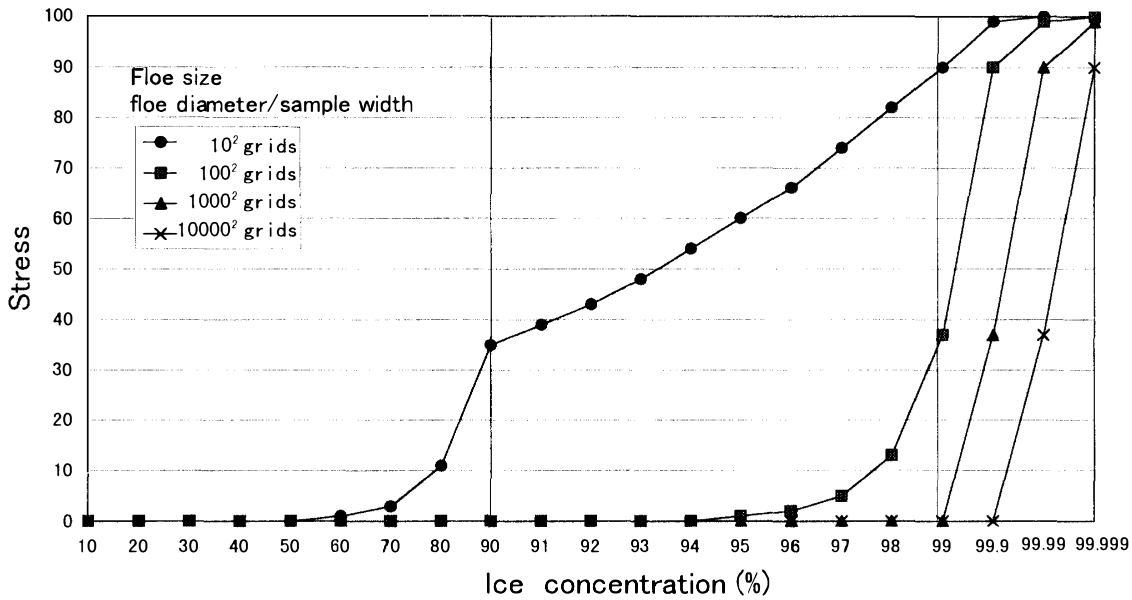

Fig. 2. Uni-axial test of ice-covered sea with small floes.
The stress is recorded shortly after the start of the experiment before strain hardening or lateral motion takes place. The stress is non-dimensional: the stress an ice-covered sea consisting of a single solid ice floe (N = 1, concentration = 100%) shows is set to 100.

3.3. Coagulation of floes

Grids coalesce with each other as they form large floes. Coagulation is done stepwise. The total number of grid boundaries, where grids occupied by ice contact each other, is counted. As a first step, 10% of such boundaries are randomly selected and the floes are coalesced there. The contact is perfect where adjacent grids are spanned by a single floe, and no coagulation takes place at all at the remaining boundaries; an individual boundary never undergoes partial adherece.

A grid without ice in it never freezes up throughout the experiment. If freezing were allowed, the concentration over the entire area would reach the value of 100% in a short time. This would become a different investigation, which might be treated on an other occasion.

Another 10% of boundaries coalesce in the next step, so that 20% of boundaries are now coagulated. Coagulation proceeds in this manner until all the boundaries are solid after the tenth step. One of the results is shown in Fig. 3.

The increase in floe size is small, when the concentration is small. This is due to the small number of total contact boundaries. Even with high concentration, the increase is slow at the beginning of coagulation. Unless a majority of the boundaries become solid, the floe size does not change drastically. Only the case in which all of the boundaries are solidified, will be used in the discussion below.

With high ice concentration the coagulation produces large floes as expected. However, the mean diameter is increased by one order of magnitude only. The maximum diameter detected during the experiment, not shown in the figure, was as much

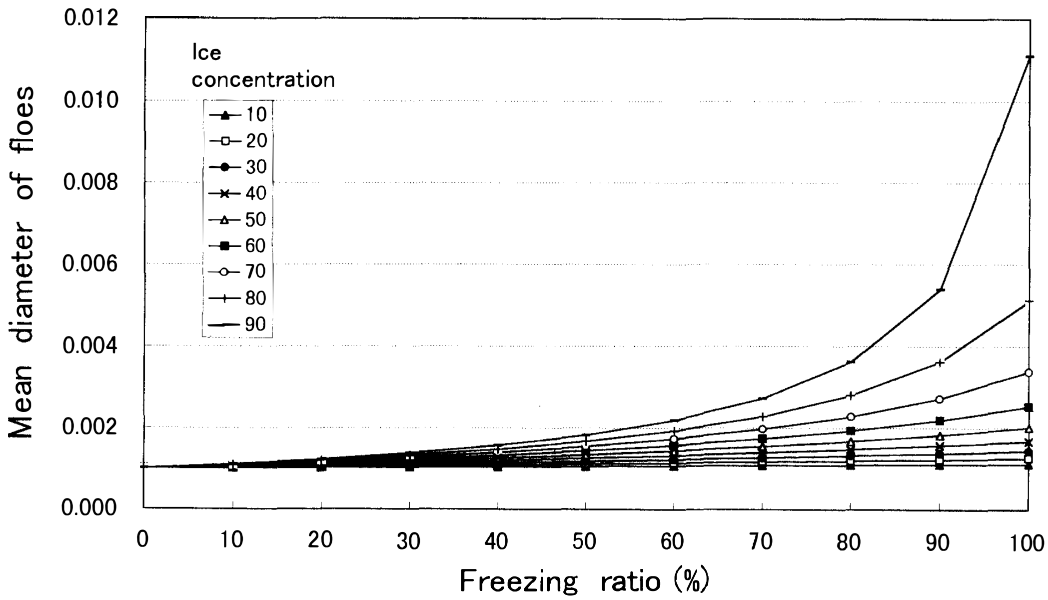

Fig. 3. Coagulation of floes without motion.
The area is divided into 1000^2 grids. The coagulation ratio is the number of hardening up boundaries divided by the total number of boundaries, where only boundaries with ice grids on both sides are counted.

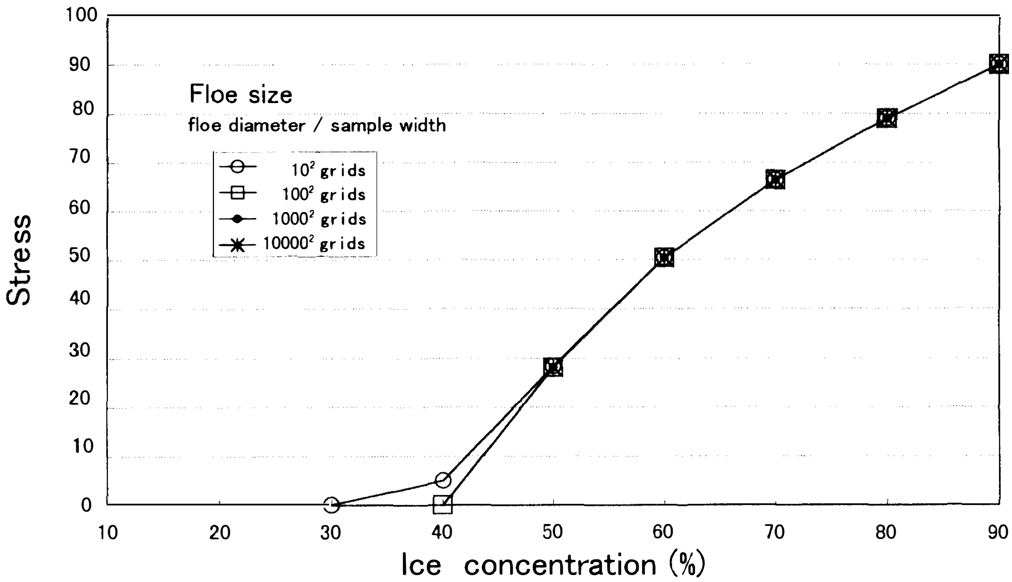

Fig. 4. Uni-axial test of ice-covered sea with large floes.
The stress is recorded shortly after the start of the experiment before strain hardening or lateral motion takes place. The stress is non-dimensional: the stress an ice-covered sea consisting of a single solid ice floe (N=1, concentration=100%) shows is set to 100.

as 10^2 times the grid size, but no more. The coagulation alone does not build up a large floe, once the ice is broken up into small pieces.

3.4. Large floes

A uni-axial compression test is done using the samples containing large floes, which were prepared by the coagulation of grid boundaries as described in the previous section. The results are shown in Fig. 4, and are to be compared with those in Fig. 2.

The sea with as little as 30 to 40% of ice cover reacts to the compression. The coagulation has indeed hardened the sample. This can be expressed in an other way. A sea surface containing less than 30% of ice cannot be regarded as an ice-covered sea in a mechanical sense.

Initial division of the area does not seem important. The mean floe size is, however, dictated by the initial division. The strengthening is not done through growth in the floe size only, but the distributions of floe size and shape seem to be the essential factors; all floes in the samples tested in 3.2 had identical sizes and shapes.

4. Dynamic Coagulation of Floes

Large floes were formed through coagulation, but only to a limited extent depending on the initial floe size. The coagulation was static; two grids both containing ice but with a water grid inserted between them never had an opportunity to come together. Motion is introduced this time to remove the obstruction.

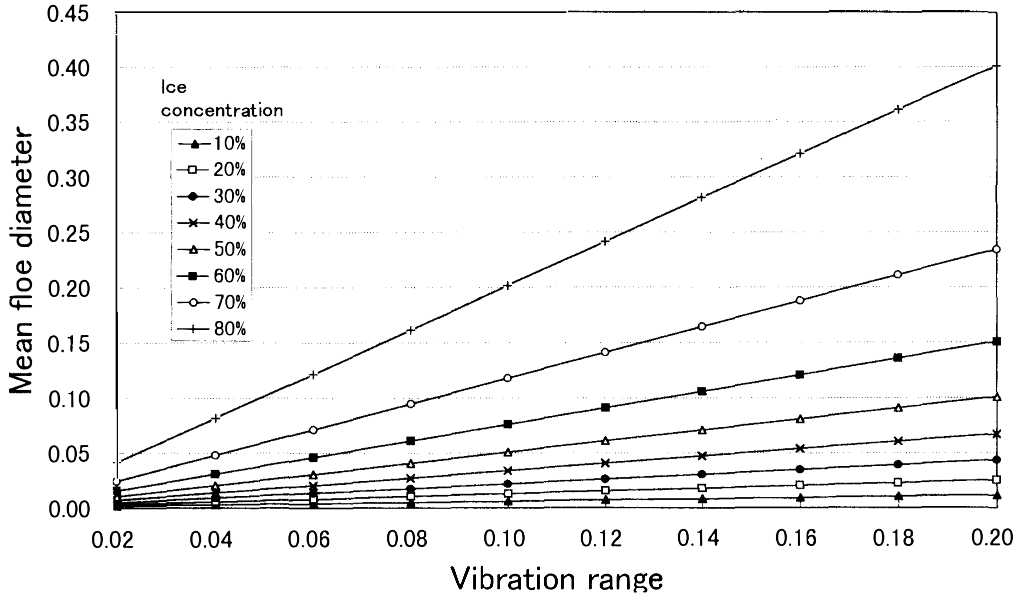

Fig. 5. Coagulation of floes in motion.
The area is divided into 1000^2 grids. The coagulation ratio is 100%. Vibration range is the mean vibration diameter of all floes in the area.

Small floes are vibrated, each in a different manner but with its original position as the center. The vibrations are random in terms of amplitude and frequency. The mean of the distance a floe travels, between successive passes through the vibration center is measured for each grid. This distance is called the vibration diameter, and serves as a measure of the vibration. The mean of the vibration diameter within the area, *i.e.* of all floes, characterizes the degree of motion. There is no particular orientation, in which the motion prevails. The motion of floes is not synchronized.

A pair of floes may come in contact through vibration. Immediate coagulation takes place at the instantaneously contacting boundary. The newly built-up floe vibrates further and may come into contact with a third floe. The sample is left in vibration for a sufficient length of time. The mean size of the resultant floes is measured. Figure 5 shows part of the results.

The resultant floe size increases more for large vibration. Increase is rapid for large ice concentration. There are no distinct difference between diagrams for different initial floe sizes.

The study showed that large floes born through a combination of motion and coagulation. An interesting point which requires further investigation is the time the process requires.

5. Conclusions

A numerical experiment on sea ice has revealed the importance of floe size in ice dynamics. Cohesionless small floes cannot resist compression; however dense they are placed together. Irregularly shaped floes of mixed sizes resist compression effectively. However, sea containing ice cover of 30% or less never resists compression and is mechanically equivalent to an ice-free sea. Large floes can be built up through coagulation of adjacent small floes. The resultant floe size is however limited depending on the ice concentration and on the initial floe size. When the coagulation is promoted by oscillatory motion by ice floes large floes can be created even when initial floes are small.

Floes are changing their size and shape all the time. Breaking of a floe reduces floe size. This is a mechanical phenomenon. Growth of floe size through coagulation is, on the other hand, primarily a thermal phenomenon. However, the kinematics of the field was found to play an important role also in this phenomenon. The change of floe size is thus dictated by the mechanical circumstances in both reduction and growth, and the floe size is an important factor in ice dynamics in turn.

(Received February 26, 1998; Revised manuscrit accepted March 24, 1998)