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Numerical study on c-axis orientations of sea ice surface grown under calm sea conditions using a particle method and Voronoi dynamics ☆

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ABSTRACT

Physical properties of frazil and grease ice depending on their microstructures are not easily measured, while they are important elements for predicting their behavior on the ocean surface. Thus, numerical models considering the effect of the microstructures are required to investigate the ice–water mixture. In this paper, we combined a computational fluid dynamics (CFD) and crystal growth model, and numerically predicted a process of flotation and accumulation of crystal nuclei near the surface of calm sea, and their growth after the accumulation. The results obtained showed that the crystal fabrics and c-axis distributions had good similarity with those of an actual sea ice, and the combined model was effective for dealing with ice–water mixture. Thus far, while we have paid little attention to the details of c-axis distributions within the surface layer of sea ice because of their tedious investigation, the results also indicated that anisotropic growth of crystal nuclei, as well as the flotation and accumulation, strongly affects the c-axis distributions within the horizontal cross-sections of the surface layer of sea ice grown under calm sea conditions. This work would be an important step for the development of numerical models to predict the complex phenomena of sea ice depending on the microstructures, such as behavior of the ice–water mixture on the sea surface.

1. Introduction

Sea ice is mainly comprised of pure ice crystals arranged in an hcp lattice and brine inclusions. They influence mechanical (e.g., Cole, 2001; Schulson, 1999; Zhang and Wilson, 1997), thermal, and other properties (e.g., Gow and Tucker, 1991) of sea ice, thus requiring detailed studies. However, the characteristics of sea ice can be considerably altered by changes in the growth conditions and the environment in which it exits (e.g., Eicken, 2003; Golden et al., 1998; Jones et al., 2012; Weeks, 1998; Weeks and Ackley, 1986); this fact makes it difficult to perform experimental studies under laboratory conditions.

In many cases, sea ice growth initiates from the ice crystal nuclei generated in supercooled seawater (e.g., Eicken, 2003; Weeks and Ackley, 1986). Nuclei grow into spherical and then discoidal crystals before forming a dendritic shape, and float to and accumulate near the sea surface (e.g., Weeks and Ackley, 1986). In leads and polynyas, generation of frazil ice is an important formation mechanism of sea ice (e.g., Martin, 1981; Skogseth et al., 2009; Smedsrud and Skogseth, 2006; Ushio and Wakatsuchi, 1993), and solid fraction of the grease ice formed by their accumulation is matter of deep interest (e.g., Maus and De La Rosa, 2012; Naumann et al., 2012); however, it is fiendishly difficult to measure. Thus, numerical models to investigate the solid fraction would be useful and powerful tools in the studies of ice–water mixture.

A number of numerical models have been developed. For example, Petrich et al. (2006) used a computational fluid dynamics model to simulate the unidirectional growth of sea ice and successfully obtained c-shape profiles of salinity, which are typically observed in first-year sea ice (e.g., Eicken, 2003; Gow and Tucker, 1991). Maus and De la Rosa (2012) developed mathematical model to predict salinity and solid fraction of frazil and grease ice, and successfully reproduced them. In their model, however, seawater solidification processes were predicted using a continuum approximation and the orientation of each crystal was not considered. The amount of seawater in the grease ice would be influenced by changes of the geometry of ice nuclei accumulated near the sea surface. Thus, growth rate anisotropies of the nuclei have to be considered to predict the amount of seawater trapped in the ice; that is, we require the consideration of crystal orientations in the numerical models.

The crystal fabric of typical first-year sea ice is known to show fine grains in the uppermost surface and columnar-shaped grains below it. This transition in the shape and size of grains accompanies a change in c-axis orientations. In other words, the c-axes of crystals show various directions within the layer of fine crystals and gradually align in the horizontal direction within the layer below with depth. The mechanisms of the transition process of c-axis orientations to the horizontal

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direction are known as geometric selection (e.g., Weeks and Ackley, 1986; Weeks and Wettlaufer, 1996); however, little attention has been paid to the c-axis orientations within the layer of fine grains near the sea surface. A reason for this is that the diameter of grains in this layer is usually <5 mm and such fine grains are tedious to investigate using traditional experimental methods in glaciology (Weeks and Wettlaufer, 1996).

Kawano and Ohashi (2009) have conducted numerical simulations of the development of the crystal fabric of sea ice using the Voronoi dynamics technique (Ohashi et al., 2004). In the model, the development of the crystal fabric was represented by the growth of crystal nuclei that had an anisotropic growth rate, and alignment of c-axes within the horizontal plane by geometric selection was obtained. In the simulation, however, the positions of crystal nuclei were fixed and their orientations, that were randomly selected, also remained at their initial states, and the flotation and rotation of crystal nuclei during their growth were not considered.

Recently, Dempsey et al. (2010) introduced the effect of rotation of crystals into the Voronoi dynamics technique, and successfully reproduced the development process of the crystal fabric of platelet ice. In their model, the process of flotation of platelets was ignored, and only the rotation after flotation was considered; each platelet rested at the orientation where three or more points on the surface were in contact with the bottom of the sea ice. Thus, the orientations were decided only by the mechanical stability, and the effects of fluid dynamics and buoyancy on platelets were not directly considered (Dempsey et al., 2010).

In this study, we first employed a computational fluid dynamics (CFD) model to represent a process of growth and accumulation of crystal nuclei with their flotation driven by the buoyancy, and simulated the formation process of the layer of fine crystals under calm sea conditions. However, the CFD simulation is computationally expensive; we conducted it by a two-dimensional approximation. We second investigated each c-axis orientation of crystal nuclei in the accumulated layer near the sea surface, which was predicted by the above flotation and accumulation simulation, and we adapted the c-axis orientations to the initial crystal nuclei; a development process of sea ice crystal from the crystal nuclei was represented in the three-dimensional simulation space, using the Voronoi dynamics technique. Finally, we obtained numerical results for the development process of sea ice crystals from the sea surface and compared the c-axis distributions obtained with simulations and experiments (Weeks and Ackley, 1986), and validated the numerical models and investigated c-axis distributions near the sea surface.

2. Numerical procedure

2.1. Nucleus flotation model

We employed the moving particle semi-implicit (MPS) method to represent flotation of crystal nuclei growing in the seawater. The MPS method was developed by Koshizuka and Oka (1995) and as a particle method for the incompressible fluid analysis. In the MPS method, continuums are represented by moving particles which are calculation points, i.e., the view point is Lagrangian. The MPS method has advantages compared to traditional finite element (FEM) methods or finite difference methods (FDM); computational grids are not necessary, interfaces can be easily tracked, and large deformations of continuums are easily represented. Thus, it has been applied to simulations of complex phenomena such as breaking waves (e.g., Gotoh and Sakai, 2006; Koshizuka et al., 1998), vapor explosions (e.g., Koshizuka et al., 1999), and fluid–structure interactions (e.g., Koshizuka and Oka, 1995; Lee et al., 2007), as well as the incompressible fluid simulations. The MPS method would also be a suitable for the simulations of flotation of crystal nuclei growing in the seawater; that is because the method can easily track the moving interfaces of ice–water and water–atmosphere, and represent the interaction between crystal nuclei and seawater. The procedure was explained below.

2.1.1. MPS method for incompressible fluid

To represent flotation of crystal nuclei in the seawater, the Navier–Stokes equation, given as follows:

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\vec{u} + \vec{g} \tag{1}$$

was solved with the incompressibility condition by using the MPS method (Gotoh and Sakai, 2006; Koshizuka and Oka, 1996; Koshizuka et al., 1998), where $\vec{u}$ is the velocity vector, ρ is the density of the element at a position, P is the pressure, ν is the kinematic viscosity, and $\vec{g}$ is the acceleration due to gravity. Eq. (1) is written for an element at a position. In the simulation, the continuum was discretized by three types of particles: water, ice, and wall, and each particle has a density ρ in accordance with the individual particle type. That is, the element and ρ are changed with changing the position. The flow of sea water can be represented by solving Eq. (1) with the MPS method, while a solid–liquid interaction model is also necessary to represent the flotation of crystal nuclei. The procedure for solving Eq. (1) with the MPS method was explained in this section, and the solid–liquid interaction model was described in Section 2.1.3.

In the MPS method, Gradient and Laplacian operators in Eq. (1) are discretized by following particle interaction models (Gotoh and Sakai, 2006; Koshizuka and Oka, 1996; Koshizuka et al., 1998):

$$\langle\nabla\phi\rangle_i = \frac{d}{n^0}\sum_{j\neq i}\left[\frac{\phi_j-\phi_i}{\left|\vec{r}_j-\vec{r}_i\right|^2}\left(\vec{r}_j-\vec{r}_i\right)w\left(\left|\vec{r}_j-\vec{r}_i\right|\right)\right], \tag{2}$$

$$\left\langle\nabla^2\phi\right\rangle_i = \frac{d}{\lambda n^0}\sum_{j\neq i}\left[\left(\phi_j-\phi_i\right)w\left(\left|\vec{r}_j-\vec{r}_i\right|\right)\right], \tag{3}$$

$$\lambda = \frac{\sum_{j\neq i}\left|\vec{r}_j-\vec{r}_i\right|^2 w\left(\left|\vec{r}_j-\vec{r}_i\right|\right)}{\sum_{j\neq i} w\left(\left|\vec{r}_j-\vec{r}_i\right|\right)}, \tag{4}$$

where d is the number of space dimensions, ϕ is an arbitrary scalar, $\vec{r}$ is the position vector of a particle, w is the weight function, λ is the parameter that ensures that increases in variance are equal to the analytical solutions, n^0 is the constant value of the particle number density fixed for incompressibility, i is the number of a particle, and j is the number of a neighbor of the particle i. The particle number density for particle i is defined as follows:

$$n_i = \sum_{j\neq i} w\left(\left|\vec{r}_j-\vec{r}_i\right|\right). \tag{5}$$

The weight function employed in this study is defined as follows (Shao and Lo, 2003):

$$w\left(\left|\vec{r}_j-\vec{r}_i\right|\right) = \begin{cases} \frac{40}{7\pi r_e^2}\left(1-6\left(\frac{\left|\vec{r}_j-\vec{r}_i\right|}{r_e}\right)^2+6\left(\frac{\left|\vec{r}_j-\vec{r}_i\right|}{r_e}\right)^3\right) & 0\le\left|\vec{r}_j-\vec{r}_i\right|<0.5r_e \\ \frac{10}{7\pi r_e^2}\left(2-2\left(\frac{\left|\vec{r}_j-\vec{r}_i\right|}{r_e}\right)\right)^3 & 0.5r_e\le\left|\vec{r}_j-\vec{r}_i\right|<r_e \\ 0 & r_e\le\left|\vec{r}_j-\vec{r}_i\right| \end{cases} \tag{6}$$

where r_e is the finite distance of interaction between particles. Ataie-Ashtiani and Farhadi (2006) conducted dam-break simulations using the MPS method, and compared the stability of the calculations