

# Ice Conditions in an Anisotropic Sea Ice Dynamics Model

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## ABSTRACT

**An oriented ice thickness distribution is presented. It describes sea ice as an oriented material and provides the description of ice conditions for an anisotropic plasticity model. This model describes the formation and evolution of individual lead and ridge systems. We can resolve ice behavior on scales as small as a few kilometers. Ship navigation and other off-shore operations should benefit from the added information provided in simulations and forecasts of lead and ridge orientations.**

## INTRODUCTION

Ice observations throughout the polar regions provide fractions of area covered by ice of different stages of development (thickness). Ice charts produced by the U.S. Joint Ice Center classify ice into the categories: Open water and new ice (0-10 cm), Young ice (10-30 cm), First year thin (30-70 cm), First year medium (70-120 cm), First year thick (120-200 cm), and Old ice (survived at least one summer's melt). The Russian ice observation system is similar, but adds a separate category for open water. The Canadian Ice Centre is similar, but divides New ice into New and Nilas ice, and divides Young ice into Grey (10-15 cm) and Grey-white (15-30 cm). Additional information on the size of ice floes can be added to an ice chart, but it will not be discussed here because sea ice dynamics models cannot now provide such information.

Thorndike et al. (1975) introduced the ice thickness distribution to describe ice condition. They introduced a probability density function  $g(h, \mathbf{x}, t)$  as the fraction of area with thickness greater than  $h$  but less than or equal to  $h+dh$  in the neighborhood of location  $\mathbf{x}$  at time  $t$

$$\int_{h_1}^{h_2} g(h)dh = \frac{1}{R}A(h_1, h_2)$$

where  $R$  is the area of the neighborhood and  $A$  is the area covered by this category of ice. The thickness distribution evolves thermally and mechanically according to:

$$\frac{\partial g}{\partial t} = -\nabla \cdot (\mathbf{v}g) - \frac{\partial}{\partial h}(fg) + \psi \quad (1)$$

where  $f$  is thermal growth rate and  $\psi$  is the redistribution function. The redistribution function describes the formation of water during opening, and the ridging of thinner ice into thicker ice during closing. This classical description includes the discrete classifications used by ice observers, and when numerical solutions are obtained, the thickness categories can match those used by observers. The thickness distribution evolves as the ice cover

deforms and by thermal growth or melt. The thickness distribution was introduced as part of the Aidjex elastic plastic ice dynamics model (Coon et al., 1974). Hibler (1979) used thickness distribution in a viscous plastic model, and Pritchard (1981) used it in a modified and extended Aidjex model. Most of the recent large-scale sea ice behavior models use a reduced thickness distribution (two categories: open water and thick ice). A few exceptions appear: e.g., Pritchard et al. (1990) described a coupled ice ocean model developed to forecast ice edge behavior; and Flato and Hibler (1995) extended the thickness distribution to describe ridged and undeformed ice separately. All of these models describe ice as an isotropic material.

More recently, Coon et al. (1992, 1997a, b) introduced an anisotropic plasticity model that accounts for formation and evolution of individual lead systems directly. In their model, ice is composed of *oriented* ice and *isotropic* ice. The *oriented* ice is created when a lead system forms. The oriented ice condition is defined by its thickness distribution and its lead direction. This ice evolves mechanically and thermally. It can become a ridge if compressed. The *isotropic* ice is the surrounding older, thicker ice. It has no orientation. It is composed of floes and inactive ridges. It contains cracks from thermal stresses and isostatic imbalance. Efforts to develop the anisotropic plasticity model have focused on describing the yield surface and flow rule of a new lead, on the changes to the yield surface as ice grows in the lead and it is deformed, and on the rules for describing how a new lead forms. Less attention has been given to behavior of the isotropic ice. A yield surface and flow rule have been prescribed, but they have assumed that the yield surface for isotropic ice changes only a little and slowly.

In the present paper, I propose that all sea ice is oriented. It may begin as a lead system (either an individual lead or a set of parallel leads), which is obviously oriented, or it might begin as an open water area, which I interpret as equal amounts of ice having all orientations. This state is therefore isotropic. I lay a mathematical framework needed to describe the formation of open water during isotropic opening, a deformation state not considered by Coon et al. (1997a, b). In addition, the new oriented thickness distribution provides a basis for estimating compressive strength in each direction consistently.

## ANISOTROPIC ELASTIC PLASTIC MODEL

Coon et al. (1992) introduced a method for incorporating the behavior of individual leading, rafting, and ridging events into the large-scale constitutive behavior of pack ice. The idea is that the

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