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Modelling the rheology of sea ice as a collection of diamond-shaped floes

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Abstract

In polar oceans, seawater freezes to form a layer of sea ice of several metres thickness that can cover up to 8% of the Earth's surface. The modelled sea ice cover state is described by thickness and orientational distribution of interlocking, anisotropic diamond-shaped ice floes delineated by slip lines, as supported by observation. The purpose of this study is to develop a set of equations describing the mean-field sea ice stresses that result from interactions between the ice floes and the evolution of the ice floe orientation, which are simple enough to be incorporated into a climate model. The sea ice stress caused by a deformation of the ice cover is determined by employing an existing kinematic model of ice floe motion, which enables us to calculate the forces acting on the ice floes due to crushing into and sliding past each other, and then by averaging over all possible floe orientations. We describe the orientational floe distribution with a structure tensor and propose an evolution equation for this tensor that accounts for rigid body rotation of the floes, their apparent re-orientation due to new slip line formation, and change of shape of the floes due to freezing and melting. The form of the evolution equation proposed is motivated by laboratory observations of sea ice failure under controlled conditions. Finally, we present simulations of the evolution of sea ice stress and floe orientation for several imposed flow types. Although evidence to test the simulations against is lacking, the simulations seem physically reasonable.

Keywords: Sea ice; Stress; Anisotropy

1. Introduction

In polar oceans, seawater freezes to form a layer of sea ice of several metres thickness that can cover up to 8% of the Earth's surface. The sea ice cover consists of sea ice floes, with a lateral scale of 0.1–5 km, separated by long, thin regions of open water or weaker ice called leads whose length can span may floe widths. Sea ice plays a significant role in determining polar and global climate and Global Circulation Models (GCMs) used for climate prediction incorporate representations of sea ice dynamics and thermodynamics. Here, we focus on sea ice stresses that develop during deformation of the sea ice cover.

At the scale of a floe, the velocity field is typically discontinuous and local stresses are heterogeneous and anisotropic. However, from observations it has been found that the lead density is around 1 km of lead length per 1 km^2 of sea ice area [7], so that on the larger scales relevant for GCMs, e.g. 100 km, where many leads are present, sea ice stresses can be determined by averaging over the stresses in many floes. Consideration of the relationships between mean sea ice properties has led to the development of continuum models of sea ice dynamics such as the AIDJEX model [1]. With the exception of [20] and [21], who considered the role of aligned leads in the sea ice cover, GCM-type models of sea ice dynamics have neglected the role of anisotropy in determining sea ice stresses, even though observations reveal there is a strong bi-modality in the distribution of leads at length scales as small as 20 km [7]. Ice floes delineated by active leads have a diamond shape with the angle between the floe edges having slightly different, but persistent, values of 30°–40° [2,15] or 40°–70° [7]. This characteristic ice floe shape appears to be independent of spatial scale over the range 10–150 km [15,19].

The deformation of a consolidated (unbroken) region of sea ice can be divided into two stages [14]: the first stage involves a local stress build-up in the ice cover driven by imposed atmospheric and/or oceanic stresses, is relatively short in duration, and results in the propagation of cracks that split the ice cover

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