Issues in Large-Scale Sea Ice Dynamics Modeling

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SUMMARY

Capabilities to model sea ice dynamics have grown substantially over the last few years. As a result, users now face many decisions when choosing an appropriate mathematical model for a specific application. Models share the purpose of simulating ice motion, but on different time and space scales. Although development of these models has been aimed at different applications, models do appear to be reaching a stage of maturity where they have many common features. In this review, we examine various application needs, and describe the range of important features available in a variety of geophysical scale ice behavior models, to enable the user to make an intelligent model choice.

The range of applications requiring choice of a model by the user may widely vary. For instance, a great amount of uncertainty in motions of the sea ice cover makes modeling of general scientific interest. To gain basic scientific understanding of the behavior of sea ice requires knowledge of all external forces as well as the constitutive relationship between internal stress and deformations and therefore models are helpful. These motions are also of engineering importance because of ongoing petroleum development along the North Slope of Alaska. Ice motions are of direct importance, because oil spilled in the ice would be transported by the motion of the ice cover. The geophysical scale forces from winds and currents over wide areas of the ice pack cause motion which can be transmitted over large distances when internal ice stress is large. The ice stress transmitted shoreward can generate forces on any drilling structures positioned there. On scales of a hundred meters and less these forces affect the design and use of these offshore drilling structures. Artificial islands, docks and breakwaters, and conical platforms must therefore be designed to withstand the forces that sea ice can apply. Other engineering and operational applications include warning of possible ice invasions during petroleum drilling operations in open water conditions. Also at scales of hundreds of kilometers resolution, sea ice behavior affects climate dynamics, where the effects of sea ice motion and deformation are felt primarily through the generation of open water that increases heat transfer from the atmosphere to the ocean. Here, ice stress is not of direct physical concern. Ice stress does, however, play a role in estimating noise generated by the ice cover, still another possible application for an ice motion model.

From these examples, it is obvious that time and space scales in each of these problems can differ significantly. In addition to different time and space scales, important properties of ice behavior can differ depending on the location. For example, the Arctic basin, including the Beaufort and Chukchi Seas, is dominated by thick ice and by ice stress divergence. At lower latitudes, including the Bering Sea and the Labrador Sea, the presence of more open water and thinner ice makes other driving forces, such as ocean currents, more significant than ice stress. In smaller scale problems, such as navigation within the Canadian Archipelago, ice stress is dominant. It is apparent that while no single model can be expected to be ideal for all these applications, the basic physical processes that occur are similar and can be described by appropriate parts of the different models.

In order to select an appropriate model to match the specific application, one must be able to ensure that an adequate level of performance can be met. Recently, the process of measuring performance has been addressed. As part of this process, one must decide which variables are of interest. Is ice velocity important? Must the ice motion be estimated by accumulating velocities over long periods of time? Are ice conditions and their changes of substantial interest? Are ice stresses important variables? Each of these variables may, to some extent, be compared with observations. Some of these require comparison with remotely sensed images and tend to be more qualitative in nature. Other comparisons, such as ice velocity, can be observed directly by comparing with drifting buoys, and statistical correlations can be made. Once these questions are answered, the user can begin to review the range of features offered by various models.

Before describing these features, however, we feel one important point must be made. That point centers around the need to separate the physics of ice behavior from the numerical considerations needed to obtain solutions of the mathematical models describing this behavior. In the past, many models have been presented without separating physics from numerics, and as a result, confusion and unnecessarily restrictive models have developed. We have identified the need to separate physical from numerical considerations to allow the user the broadest possible choice of models available.

There are a variety of features for ice motion models that are imperative to understand before effective model selection can be made. To begin with, these are deterministic models, where forces are identified individually and calculated directly. In addition, they are continuum models, where properties of discrete floes are averaged over the desired length scales. It is suggested that in the future, some description of discrete floe behavior be superimposed on continuum models to account for local uncorrelated floe motions at smaller scales.

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The physical behavior of the sea ice is described by accounting for mass, momentum and energy balance. In addition, the constitutive law relating stress and redistribution of ice to deformation must be given. Mass conservation can be satisfied either in the form of the thickness distribution, or by using simpler models that describe only a few components. Several formulations of mechanical redistribution of thin ice into thicker ice are described. Thermal growth and ablation of ice also changes the ice condition. Either climatological mean growth rates or thermal energy balance are acceptable formulations.

Momentum balance must account for forces exerted on the ice from winds, currents, waves, sea surface tilt, and internal ice stress. Ice cover acceleration must account for both inertia and coriolis components, and their relative importance differs with different time scales. The ocean currents provide an extremely important driving force under certain conditions. Furthermore, the ice motions and ocean currents can be dependent in each other. These models range from quadratic drag laws to coupled ocean dynamic models.

The constitutive law relating stress to deformation is assumed to be an elastic/plastic or a viscous/plastic response. Both are capable of describing the wide range of strain rates observed in the ice cover without changing material parameters in a nonphysical way. A variety of yield surface shapes are described. Each of these yield surfaces is isotropic, allows little or no tensile stress, and has a maximum compressive strength to describe rafting and ridging failure during convergence. An associated flow rule is assumed in all models. This flow rule allows dilatation to describe the large area changes that accompany failure in rafting and ridging.

Computational considerations are discussed separately. These include the choice of Lagrangian or Eulerian description, finite element or finite difference approximation, implicit or explicit time integration, and choice of elastic/plastic or viscous/plastic constitutive laws. This last choice is made more for numerical than for physical reasons.

The choice of Lagrangian or Eulerian description is made for numerical reasons in modeling sea ice dynamics. Each provides the ability to describe the ice velocity field. The Lagrangian description references each grid location to initial particle position and allows simple tracking of individual ice floes, but grids can become too distorted over long periods of time. The Eulerian description references each grid location to a fixed point in space, and thereby avoids any grid distortion, but suffers from numerical dispersion as the ice cover moves through the grid.

Different numerical schemes have been developed based on finite element and finite difference techniques. Each has advantages and disadvantages. The most valuable properties of the finite element formulation are the arbitrary connectivity of elements, the simplicity of specifying tractions on the boundaries and the wide range of potential time integration procedures. All are a matter of convenience. They do, however, increase computer costs in some applications and this sometimes makes the finite difference formulation preferable. The choice of numerical time stepping can depend on the choice of finite element or finite difference scheme. In general, it can be implicit or explicit. Again no single scheme is best for all possible applications. The time integration choice depends also on whether an elastic/plastic or a viscous/plastic constitutive law is used. For large-scale ice dynamics, a rigid/plastic model is conceptually adequate. However, to avoid difficulties in solution, it is desirable to assume small stress behavior to be either elastic or viscous.

Finally, the range of applicability of each model and its flexibility are addressed. These can impact any final decision on model choice. Demands on computer resources, including central processing times, memory, disks, and manpower needs for both program development and program operation are also considerations for choice of the codes. While peripheral calculations, such as grid generation, graphics, and data communications are similar for all models, there are some advantages in different models.

When faced with the decision of which sea ice dynamics model to use for a particular application, there are several things for the user to bear in mind. The first is a clear view of that application, and the physics that is essential in that application. Second is the series of questions which may be used to draw into focus those variables which must be included in order to ensure an adequate level of performance. Finally, the features of each model should be reviewed. Using information on key parts of the ice dynamics models and knowledge of the variety of approaches available to address each part, users will be able to choose an existing code for a specific application, or choose important features of existing codes, and adapt them for their needs.