

# **Toward Construction of an Efficient, Lead-Resolving PIPS Model**

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## **LONG-TERM GOALS**

Our long-term goals are to develop and implement lead-based sea ice rheologies into a high-resolution anisotropic sea ice model that is able to efficiently simulate and predict the initialization and propagation of oriented leads and ridges of sea ice. Our particular interest is to provide such a lead-resolving sea ice model for the Navy's Polar Ice Prediction System (PIPS) for high-resolution, large-scale sea ice forecasting. We are also interested in using the model to understand the dynamic and thermodynamic sea ice processes that trigger leads and ridges to form and propagate in time and space in relation to atmospheric and oceanic forcing. In addition, we wish to use the model to study the air-sea exchange through leads in relation to their geometry and thickness.

## **OBJECTIVES**

The Navy's next-generation PIPS aims at high-resolution (9-10 km), lead-resolving forecasts of sea ice and ambient noise in most ice-covered regions in the northern hemisphere. To help meet such a goal, we have developed mathematical formulations and numerical schemes for lead-based rheologies that may be introduced in an isotropic sea ice model to efficiently predict the formation and propagation of oriented leads and ridges of sea ice. We will incorporate the related rheologies in a 10-km high-resolution sea ice model, driven by realistic atmospheric forcing, to examine how they behave in actually simulating and predicting leads and ridges. The modeled leads will be compared with satellite observed leads or cracks.

## **APPROACH**

Sea ice is characterized by oriented leads, cracks, and ridges, which determine the anisotropic properties of sea ice flow. To completely capture the anisotropic properties of sea ice requires a fully anisotropic model with a memory of past oriented leads. This, at present, would be difficult for large-scale sea ice models to accomplish because of the lack of theoretical and numerical readiness. Our approach is based on the work of Hibler and Schulson (1997). They considered sea ice to be a composite system that consists of relatively strong thick ice embedded with weak thin-ice leads. Both

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14. ABSTRACT <b>Our long-term goals are to develop and implement lead-based sea ice rheologies into a high-resolution anisotropic sea ice model that is able to efficiently simulate and predict the initialization and propagation of oriented leads and ridges of sea ice. Our particular interest is to provide such a lead-resolving sea ice model for the Navy's Polar Ice Prediction System (PIPS) for high-resolution, large-scale sea ice forecasting. We are also interested in using the model to understand the dynamic and thermodynamic sea ice processes that trigger leads and ridges to form and propagate in time and space in relation to atmospheric and oceanic forcing. In addition, we wish to use the model to study the air-sea exchange through leads in relation to their geometry and thickness.</b>					
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the thick ice and the thin-ice leads are allowed to follow a viscous plastic ice rheology. Hibler and Schulson were then able to achieve “isotropic realizations” in “dynamically treating” the oriented leads, in which lead or ridge formation could be captured using isotropic but lead-based ice rheologies. They suggested two rheologies, related to two different conditions of anisotropic ice composite, potentially useful in estimating the occurrence and orientation of leads. One that is represented by a teardrop-like plastic yield curve, the other a lens-like plastic yield curve. An important question is: can these lead-based but isotropic viscous plastic rheologies capture the anisotropic properties of sea ice, if implemented in large-scale isotropic sea ice models? To answer this question, we wish to implement the above-mentioned rheologies, in addition to the widely used elliptical yield curve (Hibler, 1979), in a high-resolution isotropic sea ice model, and to examine the effectiveness of these rheologies in predicting the formation and propagation of leads and ridges under realistic conditions of surface atmospheric forcing. If they are effective, then they can be directly incorporated into the PIPS for lead-resolving sea ice forecasts. However, leads, cracks, and ridges are generally narrow faults, as observed through satellite images. This raises another question: what model resolution is appropriate to resolve such narrow features? In order to understand the scale effects on modeling leads and ridges, we wish to run a corresponding sea-ice model with a 40-km resolution and compare its results with those from the 10-km resolution model. Finally, we realize that great advances have been made in polar observational capabilities in recent years that have led to a rich collection of buoy and satellite observations of ice motion. It is useful to incorporate these observations in a forecast system such as the PIPS. We wish to develop a model with data assimilation capability and examine how assimilating buoy and satellite observations improves the modeling of ice motion, stress, and deformation, and therefore ice leads and ridges.

## **WORK COMPLETED**

We have developed mathematical formulations for the viscous plastic rheologies with teardrop and lens yield curves. These two rheologies, together with the elliptical yield curve, have been numerically implemented in a high-resolution (10 km, close to the current PIPS resolution) 12-category thickness and enthalpy distribution (TED) sea ice model (Zhang and Rothrock, 2001) for the Arctic Ocean. Driven by atmospheric forcing from 1987 to 1999, three model runs with these three yield curves, respectively, have been carried out. A corresponding 40-km resolution model with an elliptical yield curve has also been run. In addition, we have incorporated an optimal interpolation data assimilation procedure in a TED sea-ice model. Using this assimilation procedure, we have investigated the effects of assimilating buoy drift data and satellite ice motion data on modeling Arctic sea ice. The effects of data assimilation in the TED model have been described in a paper submitted to the *Journal of Geophysical Research* (Zhang et al., 2001). Our previous paper that describes the TED model has been published in the *Journal of Physical Oceanography* (Zhang and Rothrock, 2001).

## **RESULTS**

From those model runs, we have found that the above-mentioned three rheologies, implemented in an isotropic sea ice model with a 10-km resolution, are able to simulate the initialization and propagation of major leads and ridges, represented by strong, long shear zones, especially those initiated at coastal boundaries, as shown in Figures 1a, 1b, and 1c (see also our results reported in Overland and Ukita, 2000). This indicates that the isotropic viscous plastic rheologies are able to capture basic anisotropic properties of sea ice with sufficiently fine model resolution. The shear deformation patterns created by these three different rheologies are not necessarily the same. Some leads or ridges they create are simi-

lar, some differ. Therefore additional investigation is necessary to determine which rheology is relatively more realistic. With the 40-km resolution, the model either fails to capture some of the major leads that are seen with the 10-km model, or creates shear zones that are less sharp (Figure 1d). This stresses the importance of model resolution for predicting ice faults.

We have also found that assimilating ice motion observations in the TED model significantly improves the modeled ice motion with a reduced error and an increased correlation with observations. Data assimilation also considerably increases ice deformation and, hence, ice lead opening and ridging, as shown in Figure 2. The assimilation-enhanced ice lead opening and ridging in turn result in more spatial variability of ice thickness that agrees better with the observed ice thickness taken along four tracks of recent (1993–1997) submarine cruises in the Arctic.

## **IMPACT/APPLICATION**

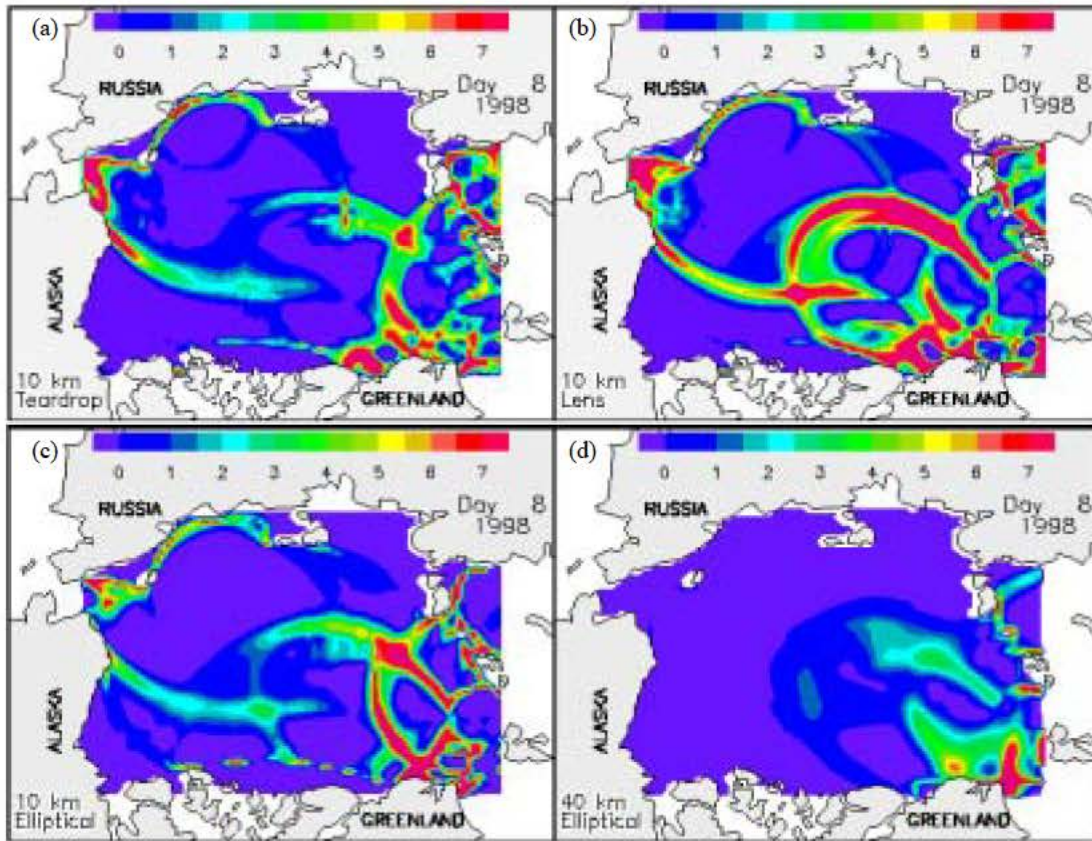
Our model results have shown that using isotropic viscous plastic rheologies in fine-resolution (in the scale of 10 km) sea ice models are likely to capture major oriented leads and ridges in the Arctic. Given that a 40-km resolution model behaves poorly in capturing narrow leads and ridges, it is suggested that using finer model resolution ( $\sim 5$  km) is likely to further improve the model's capability of resolving narrow ice faults. Our work also suggests the importance of data assimilation, which enhances the calculation of ice motion, deformation, lead opening, and ridging. Lead-resolving modeling would improve the calculation of ice dynamics and therefore forecasting of sea ice. Reliable prediction of leads and ridges is also important for the Navy's operations in the ice-covered oceans. In addition, modeling lead formation and propagation is also useful for understanding the air-sea exchange in the polar regions, which is important for climate studies.

## **TRANSITIONS**

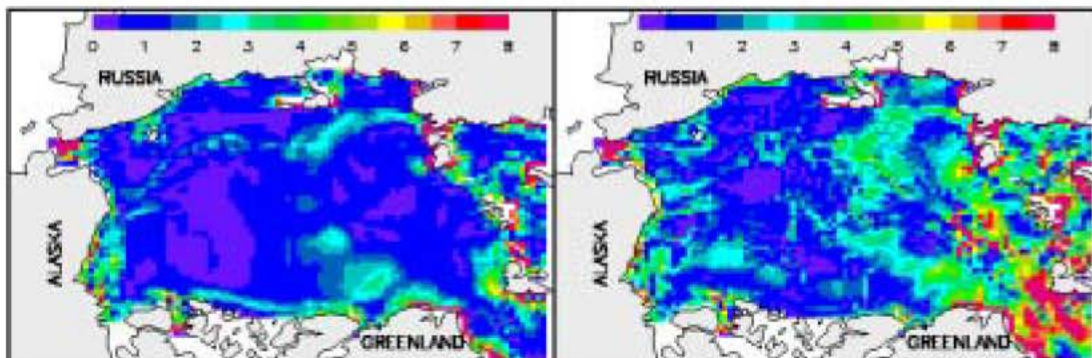
Employing the viscous plastic rheology with an elliptical yield curve, the current PIPS model, to our knowledge, uses the sea ice dynamics model that was developed by Dr. Bill Hibler and one of us (Zhang and Hibler, 1997). We have provided the PIPS model development group at the Naval Postgraduate School with a new sea ice model using an alternating direction implicit technique to efficiently solve ice dynamics (Zhang and Rothrock, 2000), which may be used in the PIPS. We will provide computer codes for the teardrop and lens yield curves to the PIPS model development group and the general sea-ice modeling community.

## **RELATED PROJECTS**

Drs. Axel Schweiger and Ruth Preller and one of us (Zhang) are investigating the effects of surface atmospheric forcing on sea ice forecasting. Accurate surface atmospheric forcing is essential to the quality of sea ice forecasting.



**Figure 1.** Modeled shear deformation (0.5%/day) of sea ice in the Arctic Ocean for January 8, 1998 using a 10-km resolution TED model with (a) a teardrop yield curve, (b) a lens yield curve, and (c) an elliptical yield curve, and using (d) a 40-km resolution TED model with an elliptical yield curve. The figure shows that the 10-km resolution sea ice model, with various viscous plastic rheologies, creates long shear deformation zones, whereas the 40-km model poorly simulates ice faults. This indicates that high-resolution models may be used to effectively simulate major oriented leads, cracks, or ridges.



**Figure 2.** Modeled shear deformation (%/day) of sea ice in the Arctic Ocean for January 1, 1993, using a 40-km resolution TED model with (right panel) or without (left panel) assimilating buoy motion and satellite ice motion data. This figure shows that data assimilation significantly enhances the calculation of ice deformation and, therefore, ice lead opening and ridging.

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