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Working Toward Improved Small-scale Sea Ice-Ocean Modeling in the Arctic Seas

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Until recently, the main motivation in sea ice modeling has been toward the development of large-scale models for climate studies. These models describe sea ice as a plastic material, with a smooth yield surface and ice strength dependent on a thickness distribution that is based on statistical representations of sea ice deformation through ridging. With tuning, they are found to reproduce ice extent and concentration in the Arctic and Antarctic, though velocity fields are overly smooth and many details, such as polynyas and leads, are not captured.

There is increasing interest in regional ice modeling. In the near-shore Beaufort and Chukchi seas, there is considerable interest from the oil industry in the formation and breakup of landfast ice, the propagation of oil spills, and prediction of sea ice conditions. The importance of resolving eddies in the ocean and modeling small-scale (sub-10-km) sea ice processes is becoming apparent, as we begin to understand the non-linear effect of small-scale processes on the large-scale motion. Recently, there have been advances in the direction of small-scale process research and regional ice-ocean model development. The most pertinent of these are outlined in this article.

Recent Progress

Small-scale ice-ocean modeling captures rich information in near-shore seas such as the Beaufort and Chukchi. *Wang et al.* [2003] present results from a nested coupled ice-ocean model with eddy-admitting resolution (3.7 km) that indicates the necessity of fine resolution for understanding coastal processes. Figure 1 shows the comparison between simulated sea ice flow (bottom) and satellite-observed water color (top) for the Beaufort-Chukchi seas in August 2000. Meso-scale eddies, which cannot be resolved in basin-scale models with course horizontal resolution, are clearly captured in the model. Furthermore, the model captures Arctic halocline ventilation along the Beaufort-Chukchi coast, which is probably induced by the oceanic upwelling driven by the Beaufort Gyre [*Wang et al.*, 2003].

In most basin-scale ice-ocean models, tidal mixing is simply ignored. In simulating ice-ocean dynamic and thermodynamic features in the coastal seas, ocean tides may be the most important mechanical mixing [*Saucier et al.*, 2003]. Figure 2 shows the seasonal variation of ocean heat flux anomaly in the Hudson Bay, subtracting a simulation with tidal forcing from one with no tidal forcing. The simulation without tides produces about 38% more sea ice. The concentration is increased along the coast and is near 100% everywhere during January to April. Both the average thickness and concentration increase. The solution without tides cannot reproduce the observed polynyas, while that with tides can. Sea ice thickness increases in the already fully covered area in the southern Hudson Bay, where tidal mixing is important alongshore. The heat flux anomaly shows that the increase in sea ice concentration and thickness is directly related to the oceanic heat flux; namely, a sensible heat flux during wintertime.

Clearly, without tides, enhanced stratification leads to more sea ice production and to the reduction of heat transfer through the water column and sea ice. The sensible heat that was stored in the initial condition remains trapped in the water column. Since tidal mixing is also important in diffusing surface heat at depth during summer time (see the positive heat flux anomaly in summer in Figure 2), the model could eventually depart from the initial condition and converge into a new steady seasonal cycle without tides, but with a reduced heat cycle and more sea ice. These results suggest that improvements in the handling of winter convection would not be able to correct the deviation of the no-tide simulation from the observations, as it would not influence the heat transfer to depth in summer.

Analysis of RADARSAT SAR imagery (Figure 3, left panel) shows sea ice deformation is localized along linear features less than 10 kilometers wide and hundreds of kilometers long. These features are distributed anisotropically [*Kwok*, 2001], with deformation occurring along preferred orientations. Observations of sea ice deformation have motivated sea ice modelers to develop anisotropic models that might better represent sub-grid scale ice deformation. *Coon et al.* [1998] developed an anisotropic rheology, with a yield surface that represents lead opening, closing, and shearing. *Hutchings and Hibler* [2002] show that intersecting sets of fracture zones may be modeled with an isotropic rheology, provided the spatial domain is discretised with sufficiently high resolution. If the sea ice is initialized to be heterogeneous at the grid scale, and is allowed to weaken in time, fractures propagate across the region in two preferred directions (Figure 3, right panel), in general agreement with an anisotropic model of sea ice with orientated flaws [*Hibler and Schulson*, 2000]. *Hopkins* [1996] has developed a discrete element sea ice model that utilizes direct simulation of rafting, ridging, and lead opening. This model shows orientated deformation, and should be helpful in developing models of ice deformation events.

One major obstacle in the development of small-scale and regional-scale sea ice-ocean models is still a lack of verification data. High-resolution (10-km) ice velocity fields are becoming available from SAR data. Buoy drift and SSMI ice velocity fields are not at high enough spatial resolution to investigate small-scale ice deformation processes. There is some debate as to how the SAR ice deformation data might be used for model validation; it is anticipated that this data will be very useful in differentiating between the various deformation models that are being developed. At present, the evolution of the ice thickness distribution is difficult to verify. However, the launch of satellites designed for ice observation (IceSat and CryoSat) will hopefully provide ice thickness monitoring for much of the Arctic Ocean. With these two data sets, and continuation of ship- and mooring-based ice observation programs, we expect to develop more realistic models and a better understanding of sea ice dynamics over the next decade. Better understanding of shelf mixing processes is expected through recent incentives to begin a long-term Arctic mooring program.

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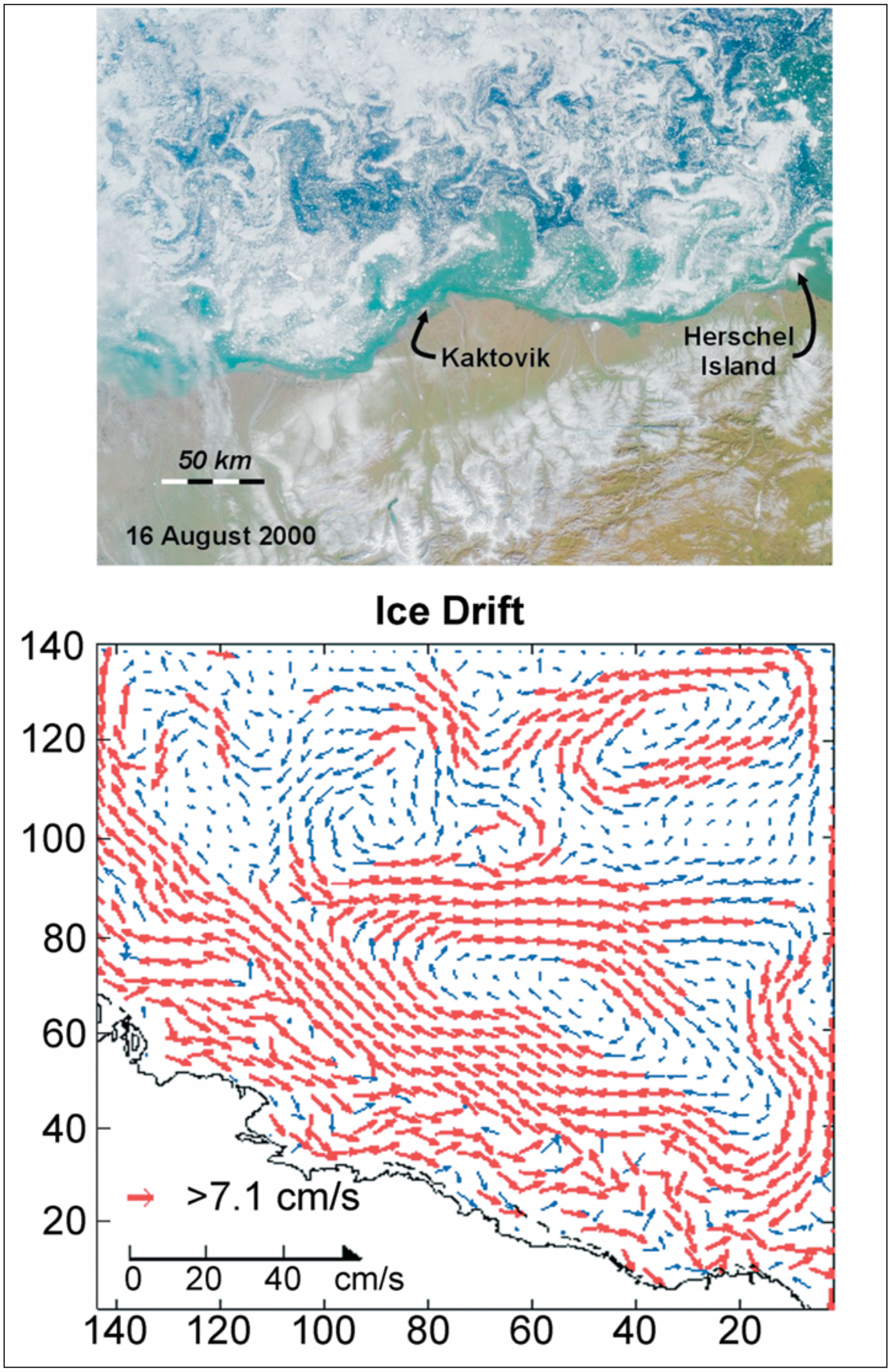

Fig. 1. Satellite-measured water color (top panel) and model-simulated sea ice velocity (bottom panel) [courtesy of Tom Weingartner, originated from JPL] in the Beaufort-Chukchi seas on 18 August 2000. Meso-scale eddies are visible from the observations, while the model captures an eastward coastal current along the Alaska coast and an offshore westward current. Off the shelf break, meso-scale eddies of sea ice are active, similar to the satellite measurement. In the bottom panel, the axes are labeled by model gridpoint (3.7 km) numbers, so the distance of the x-axis (south to north) is 520 km, while the y-axis (from east to west) distance is 700 km.

Future Directions

It has been found that high-resolution models qualitatively reproduce features such as oceanic eddies and ice fracture zones. Several points should be highlighted as important for understanding and modeling ice-ocean dynamics in coastal regions. The future direction of small-scale ice-ocean modeling can be summarized as follows.

Landfast ice presents some challenges to the ice modeling community. To correctly model the fast ice boundary requires detailed bathymetric information for the coastal sea and well-resolved coastal currents. In wintertime, the landfast ice edge provides a boundary for pack ice motion and is associated with highly localized ice and brine production in coastal leads. It has been identified that models of landfast ice extent, formation, and breakup should be developed. As a first step, existing data on fast ice extent should be compared with model output, and the prescription of fast ice boundaries based on remote sensing data or ice climatological data should be considered. The processing of the RADARSAT Geophysical Processor System (RGPS) data (Figure 1, bottom) may be extended to shore for use in the validation of fast ice models.

Satellite observations [*Kwok*, 2001] and theory [*Coon*, 1998] show sea ice to behave in a strongly anisotropic fashion, while most models used so far are isotropic. Thus, models should be developed to better capture sea ice deformation. Discontinuous Lagrangian sea ice models such as granular models [*Hopkins*, 1996] and continuum models [*Hunke and Dukowicz*, 1997] with both high-resolution isotropic and anisotropic rheologies [*Hutchings and Hibler*, 2002; *Hibler and Schulson*, 2000; *Coon*, 1998; *Pritchard*, 1998] should be validated against RGPS data. It is expected that the development of fine-resolution isotropic models, anisotropic models, and process modeling will complement each other and allow development of models for diverse applications—from climate modeling to detailed regional studies. It is generally agreed that these separate approaches should be maintained, as in the long run, they all have potential for improving our understanding of ice deformation processes.

It has been found that including more details in models can improve results. For example, coupled ice-ocean models should consider mixing driven by ocean tides and surface waves. The coupling of sea ice stress and convergence/divergence to the ocean should be taken into account. A turbulence closure model or a similar parameterization should be implemented in small-scale ice-ocean models with tidal forcing. Also, ice cover is best represented with an ice thickness distribution. In order to analyze the evolution of the ice pack in details, separate thickness distributions for undeformed and deformed ice classes should be used. Attention should be drawn to construct a physically based redistribution scheme, and to verify the redistribution parameters against field observations [*Haapala*., 2000].

Small-scale ice-ocean models require atmospheric forcing at resolutions similar to that of the model. Atmospheric forcing is usually taken from coarse-resolution re-analyses such as the National Center for Environmental Prediction and the European Centre for Median-Range Weather Forecasts re-analysis products, which when interpolated to a smaller scale, results in overly smooth fields. High-resolution re-analysis products or MM5 simulation/forecast atmospheric forcing fields are needed.

For climate atmosphere-sea ice-ocean models with grid sizes larger than 10 km, a parameterization of processes at the 10-km scale is necessary to capture anisotropic behavior. Ocean eddy resolving models may aid development of turbulent closure schemes and mixing parameterizations. The development of large-scale anisotropic ice dynamics models may be assisted by fine-resolution regional modeling and process studies. *Hopkin*'s granular model links models of processes such as rafting, ridging, shearing, and opening to larger-scale ice motion. Plastic rheological models attempt to represent these processes with a yield criterion. Both approaches should bring improvements to large-scale models.

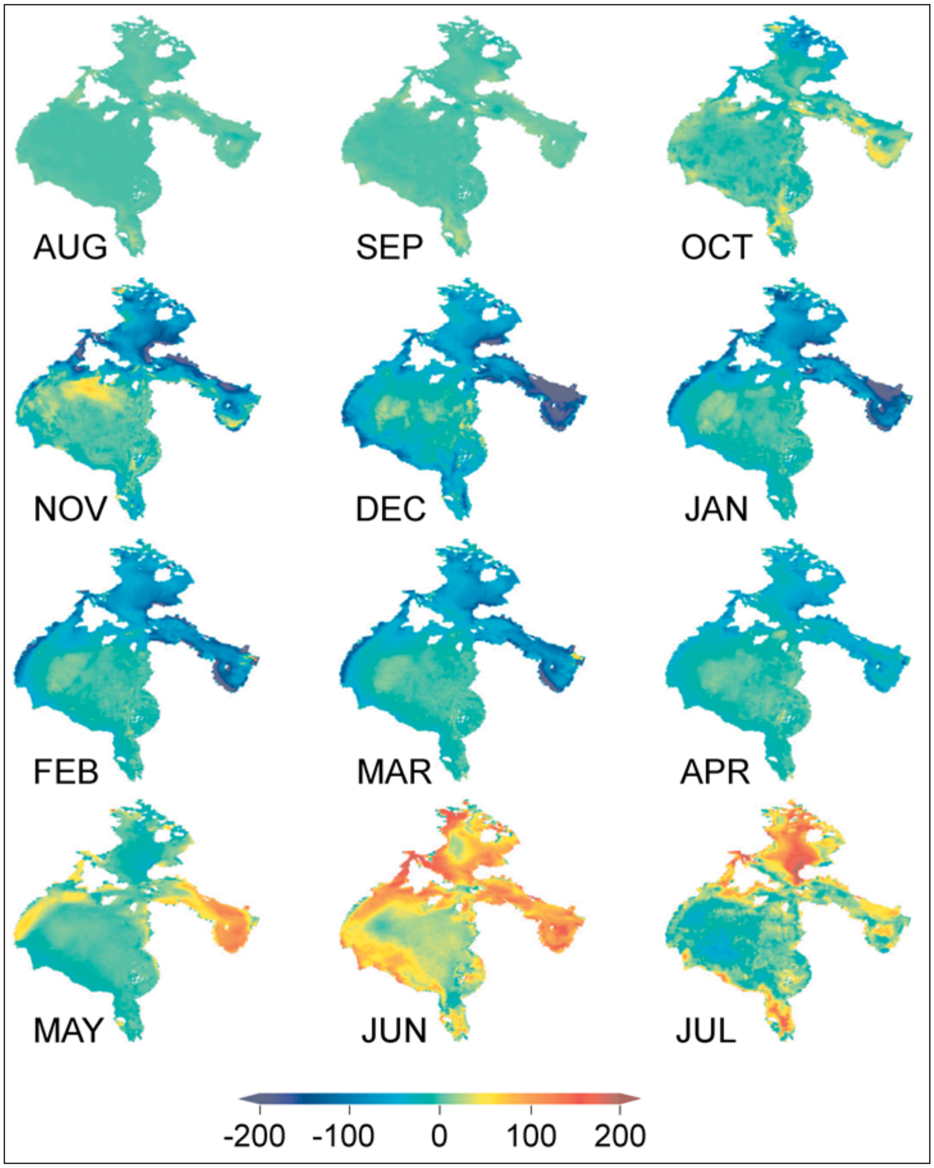

Fig. 2. The oceanic heat flux anomaly without tides (the solution with no tides minus the one with tides) in the Hudson Bay, simulated by a coupled ice-ocean model. Units are in W m². Positive value indicates stronger heat flux released by tidal mixing, and negative value indicates that less heat flux exchange between the water column and sea ice because more sea ice (higher concentration and thickness) is produced.

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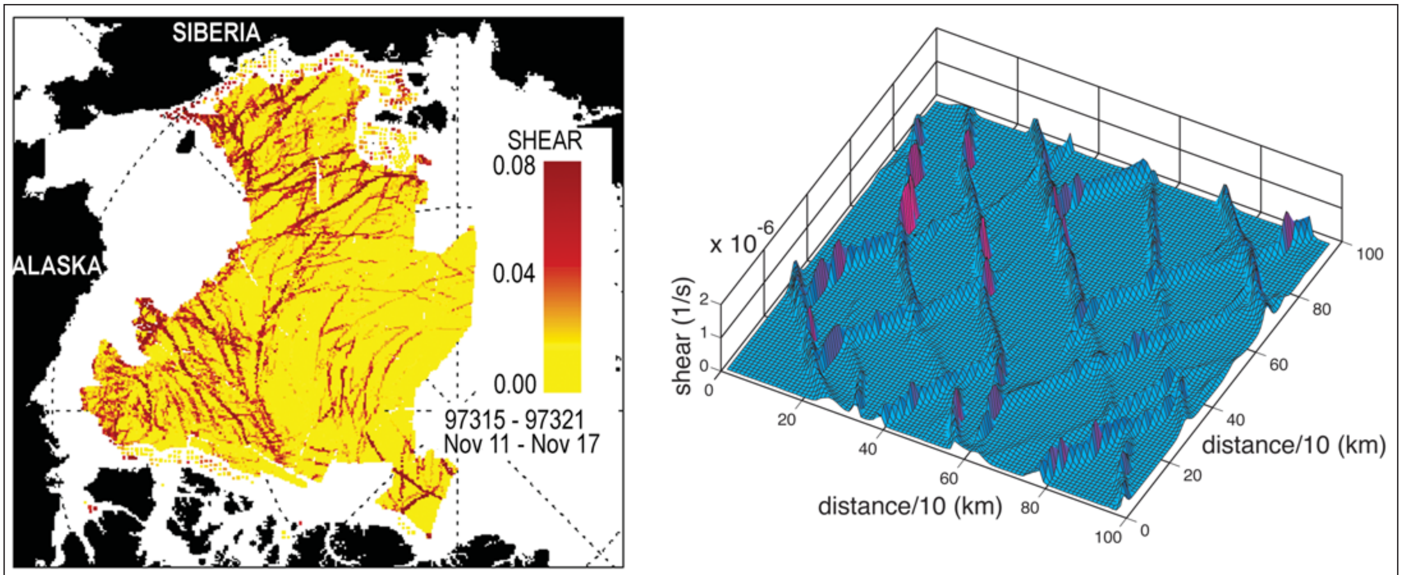

Fig. 3. (left panel) Average shear deformation of Lagragian elements (over 6 days) with dimensions approximately 10 km x 10 km on a side. The observations are based in small-scale ice motion from the RADARSAT Geophysical Processor System (RGPS). (right panel) Sea ice shear/fractures as simulated with viscous-plastic sea ice model and an isotropic rheology when spatial domain is discretised with sufficiently high resolution.

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