A New Lagrangian Model of Arctic Sea Ice

R. W. Lindsay and H. L. Stern

Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, Washington

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ABSTRACT

A new Lagrangian sea ice model for the Arctic Ocean has been developed to accommodate the assimilation of integral measures of ice displacement over periods of days or weeks. The model is a two-layer (thick ice and open water) dynamic model with 600–700 cells spaced at roughly 100 km. The force balance equation is solved for each cell with standard wind and water stress terms, a Coriolis term, and an internal ice stress term. The internal stress is found using a viscous–plastic rheology and an elliptical yield curve. The strain rate is determined by the “Smoothed Particle Hydrodynamics” formalism, which determines the spatial derivatives of the velocity by a weighted summation of the velocities of adjacent cells. A length scale of 150 km is used. The model is driven with observed geostrophic winds and climatological-mean ocean currents. Ice growth and melt are found from a seasonal- and thickness-based lookup table because the current focus is on the model dynamics. The model ice velocity simulations are compared to observed buoy motion. Over the 5-yr period 1993–97 the correlation of the daily averaged model velocity with buoy velocities is $R = 0.70$ ($N = 42 553$, rms difference $= 0.072$ m s$^{-1}$, speed bias $= +0.009$ m s$^{-1}$, angle bias $= 8.0^\circ$). This compares favorably with the correlation of a state-of-the-art Eulerian coupled ice–ocean model, where $R = 0.74$ in the summer and 0.66 in the winter over the same 5-yr period.

1. Introduction

The Arctic Ocean is an important component of the global climate system in several key aspects. Because it is ice covered, changes in the ice can produce large changes in the surface energy balance. The surface albedo, which is related to the ice thickness, snow cover, and melt pond coverage, helps determine the absorbed solar flux. The heat conductance, also related to the ice thickness and snow depth, helps determine the winter surface temperature. In the summer, the latent heat of freezing of the ice modulates the surface temperature, maintaining it very close to the freezing point.

The Arctic is not a static climate system, however. Significant changes are being observed in the air pressure (Walsh et al. 1996), air temperature (Rigor et al. 2000), ice extent (Cavalieri et al. 1999), ice thickness (Rothrock et al. 1999), and ocean circulation (Morison et al. 2000). These changes may be caused by natural variability, by anthropogenic greenhouse gases, or by a combination of these processes. Understanding the distribution and magnitude of processes that determine the ice thickness will aid in understanding these observed changes in the Arctic climate system.

We have developed a new Lagrangian dynamic ice model to improve ways of modeling ice for regional forecasting, process studies, data assimilation, and global climate forecasting. The model can be used to estimate the ice movement, deformation, thickness, and surface heat fluxes over the entire Arctic basin. A Lagrangian model can work alone or complement an Eulerian model. Some advantages of a Lagrangian model are the following:

- Data assimilation procedures for ice trajectories determined from buoys or satellite tracking are accommodated more naturally and in the process provide a unique and valuable method of model evaluation.
- Sea ice retains its identity as a material element for long periods of time and a model that recognizes this fact may have a better chance of realistically modeling ice behavior.
- Cells can be added and dropped as needed, unlike an Eulerian model in which all cells must be retained regardless of the ice extent.
- Slip lines in the ice motion are accommodated more naturally because there is no internal grid coordinate system to skew the results.
- Ice from source regions, such as a particular shelf, can be marked and traced in a more accurate manner, even with a low-resolution model.
- A Lagrangian model can change the spatial resolution as the geophysical situation requires. It can be low where there is little spatial variability and high where the spatial variability is large, such as at the ice edge.
near shore-fast ice, or in regions of strong shear. A nested-grid Eulerian model may have less flexibility.

a. A review of Lagrangian models

The model presented here follows closely on the work of others. Flato (1993) describes a Lagrangian ice model that uses the particle-in-cell (PIC) method. This method solves the momentum equation on a relatively coarse, fixed, Eulerian grid. The velocity is then interpolated to a set of Lagrangian particles that are advected individually through the model domain. He finds that the model is well suited for depicting the evolution of an ice edge and for avoiding the numerical diffusion and smoothing of the edge that is inherent in an Eulerian model. He also suggests that the PIC method could be used in a climate model and that computational savings could be obtained by increasing the spacing of the particles in regions of little spatial variability while maintaining high density in areas of interest, presumably near the ice edge or near the boundary between regions of multiyear and first-year ice.

A trio of studies by Gutfraind and Savage (1997a,b; 1998) more closely resembles what we have done. They apply a numerical technique, which was first widely used in the astrophysics community, called smoothed particle hydrodynamics (SPH; Monaghan 1988, 1992). No underlying Eulerian grid is used to determine the momentum balance. In this technique, the momentum equation is solved for individual point-mass particles. The strain rate, needed to determine the internal stress in the ice, is determined at particle positions by summing over the properties of neighboring particles. As in the PIC method, the number density of particles can be varied to meet the needs of the situation being modeled and does not need to be constant over the domain. Indeed, particles can be judiciously added or removed to meet the resolution demands for spatial variability in the model. Gutfraind and Savage defined the “ice pack density” (area density) as a state variable and used a Mohr–Coulomb type of rheology to model the internal stress, similar to that used by Flato (1993) in the PIC model. They computed the wind-driven flow of ice through a wedge-shaped channel and compared the results to those found using a discrete-element method (Gutfraind and Savage 1998). The model had only open water and ice, with all the ice 1 m thick. They also used the technique to compute the ice movement in an idealized marginal ice zone (Gutfraind and Savage 1997b).

A third related approach is that of Pritchard et al. (1990). They define an adaptive grid for the Bering Sea that deforms such that the final line of grid cells stays with the ice edge in a semi-Lagrangian manner. The grid is not entirely Lagrangian in that the grid velocity is not matched to the ice velocity at all locations and some grid points remain fixed. High grid resolution is maintained near the ice edge, the region of most interest in their study, even as the edge moves. They point out that in a rigid Eulerian grid many cells must be maintained with high resolution for all regions that might contain ice, even if no ice is in them.

Hopkins (1996) devised a dynamic model of sea ice consisting of convex polygons (floes) of multiyear ice with polygons of first-year ice in between. The floes had a mean area of 2 km² and covered 75% of the model domain. Driven by an imposed strain field, the model calculated the forces on each parcel of ice and moved them accordingly. If the motion caused ice parcels to overlap, this was interpreted as ridging, with appropriate redistribution of ice thickness. Hopkins used the model to calculate the shape of the yield surface in stress space, the energy dissipated by deformation, and the change in the ice thickness distribution. In a further study, Hopkins and Thorndike (2002) ran a 10-day simulation for the entire Arctic Ocean in which they obtained very realistic appearing fracture patterns. While the Hopkins model and our model are both discrete particle simulations, his is formulated in terms of solid mechanics in which particles have definite shapes, orientations, material properties, and interactions with adjacent particles, whereas our model is formulated in terms of fluid mechanics. In the solid mechanics formulation the particles represent distinct granules of the ice cover, whereas in the fluid mechanics formulation the particles are representative tracers for average properties of the ice over spatial scales on the order of the particle separation. The solid mechanics approach is better able to model fractures (discontinuities) by tracking upward of 50 000 particles to achieve 10-km resolution of the Arctic Ocean, at a high computational cost. For our purposes the fluid mechanics approach with 100-km resolution adequately represents the properties of interest such as ice velocity and thickness, at a relatively modest computational cost.

b. Smoothed particle hydrodynamics

The momentum equation for sea ice includes an internal stress-gradient term derived from the spatial gradients of the ice velocity, the strain rates. In an Eulerian model the strain rates are easily determined by centered differencing of adjacent cell velocities. With the Lagrangian model the cell locations change constantly and are distributed irregularly. We solve this problem through the formalism of SPH, which has been used widely to solve the momentum equation in a variety of modeling problems. It was first developed to solve astrophysical problems (Lucy 1977; Gingold and Monaghan 1977) and has now been applied (references in Monaghan 1992) to gas dynamics, stellar collisions, impacts, cloud collisions, disks and rings, jets, motion near black holes, supernovas, and special and general relativity. It has also been used for cohesive granular flow (Oger and Savage 1999) and for sea ice (Gutfraind and Savage 1997a,b; 1998). Our development of the SPH formalism follows that of Gutfraind and Savage who
FIG. 1. Contour plots of the SPH weighting functions. A typical spacing of cell locations is shown with diamonds. (a) The Gaussian function with a length scale of 150 km used for averaging or interpolation, and (b) the derivative of the Gaussian used, in this case, for the derivative in the $x$ direction.

SPH determines the local average of a smooth field quantity $f(r)$ as a weighted summation of the property at the locations of neighboring particles. The weighted sum is derived from an area integral with a kernel function $W$ (Monaghan 1988):

$$\int W(r, L) \, dr = 1,$$

where $L$ is a smoothing length. One of the most accurate kernels is the Gaussian (Monaghan 1992), and this is the kernel used in the present model, but others can be used to good advantage. For any $W$, the limit for small $L$ must be $\delta$, the Dirac delta function.

The key aspect of SPH is that the gradients of any field, such as the ice velocity, are also expressed as a summation, not with the weighting function $W$ but with its first derivative (Monaghan 1988):

$$\langle \nabla f(r_i) \rangle \approx \sum_{k=1}^{N} f_k a_i \nabla W(|r_i - r_k|, L) ,$$

where $\nabla_i$ represents the gradient with respect to the coordinates of particle $i$. Equation (4) is the heart of SPH; the spatial derivatives of the velocity (the strain rates) are computed as weighted sums over neighboring cells. For example, the SPH formulation of one element of the strain rate tensor for particle $i$ is (Gutfraind and Savage 1997a)

$$\dot{e}_{xx,i} = \sum_{k=1}^{N} a_i (u_i - u_k) \frac{\partial}{\partial x_i} W(|r_i - r_k|, L) ,$$

where $\partial/\partial x_i$ is the derivative with respect to the coordinates of particle $i$. Figure 1 shows contours of the Gaussian weighting functions for interpolation or smoothing and for determining the spatial gradients, both with a length scale of 150 km. We would like to choose a length scale as small as possible in order to simulate as much spatial detail as possible. Numerical experiments show that for a spacing of 100 km, the nominal spacing of the cells, the derivative is well estimated with a length scale of 150 km or more. The sensitivity of the error of the model velocity as compared with observed velocities with respect to the length scale (and other parameters as well) is discussed below.

SPH is used in the model to interpolate parameters, such as mean thickness or velocity, to a point and to smooth the fields by substituting the interpolated parameter for the cell value. If desired, the interpolation procedure represented by (2) can also be used to interpolate needed parameters to a fixed Eulerian grid with a smoothing length $L$ near the size of the grid spacing. SPH is also used to determine spatial gradients in the velocity. The SPH gradient procedure works accurately when the field of particles exhibits a smoothly varying property and when the particles have both a high number density in comparison with the smoothing length scale and fill the integration region. The following section describes our implementation of smoothed particle hydrodynamics.

2. The Lagrangian ice model

The model is based on a set of Lagrangian cells. The cells are considered as individual regions of ice in the
dynamic model, and each cell has an associated position \((x, y)\), velocity \((u, v)\), ice compactness \(A\), and mean ice thickness \(h\). The area of the cells is computed each time step from a Voronoi tessellation of the entire basin. The Voronoi polygon of a point contains the region closer to that point than to any other point. The parameters describing the cells are assumed to vary smoothly in space. The cells are initially given positions in a square grid with a grid spacing of \(\Delta x = 100\) km. Cells may be removed if they lose all their ice, or merged with a neighbor (averaging the positions, velocities, thickness, and compactness) if they move too close together. The minimum separation is \(0.4\Delta x\). Cells may also be created when ice forms in a formerly ice-free region, either as a result of offshore flow or from freezing in the fall. A summary of the parameters used in the model is shown in Table 1.

This first implementation of the model, focused on ice dynamics, has just two ice classes, open water and ice, following Hibler (1979), and uses a seasonally dependent ice-growth rate determined from the ice-growth table of Thorndike et al. (1975). Future versions will have a full thickness distribution and ice growth and melt rates determined from a multilayer thermodynamic model solved on a low-resolution Eulerian grid.

### a. Coastal cells

The coastal boundary condition is established by assuming the coast consists of fixed cells with very thick ice. The coastal cells have a spacing of 25 km and have an assumed area of 2500 km\(^2\) and an assumed ice thickness of 10 m. The idea is that these stationary cells will impose local strain-rate estimates via the SPH procedure that will create the necessary convergence and shear to approximate the internal ice stress in the coastal regions. The coastal cells are used in the strain-rate determinations and in interpolating ice thickness values for internal stress estimates. The thickness of 10 m is chosen to achieve the desired effect without introducing unrealistic values in the field.

### b. Stress gradients

The velocity gradients (strain rates) can be found for any location using the SPH gradient formalism (including the points with zero velocity for the coast). However, the ice stress is not defined for these coastal points, so the stress gradient is not defined for cells near the coast. This problem is overcome by determining the strain rates and stress at four points near each cell, 1/4 of the initial cell spacing in the positive and negative \(x\) and \(y\) directions (Fig. 2). The ice thickness and concentration are interpolated to the four locations as well. The ice thickness assigned to the coastal boundary points or the open ocean points is reflected in these interpolated ice thickness values. Any of the four points near a coast will have both an increased ice thickness and a strain rate reflecting the presence of the coast. The stress is determined from the strain rate at each of the four points following a viscous–plastic constitutive law. The normal and tangential forces on the cell due to internal ice stress are then determined from the gradient in the stress tensor by simple finite differences of the stress values at the four points.

The SPH formalism is open to a variety of constitutive laws to translate the computed strain rates into internal ice stress gradients. The viscous–plastic rheology (Hibler 1979; Zhang and Hibler 1997) with an elliptical yield curve is used here. Kreyscher et al. (2000) found that

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### Table 1. Model parameters: Standard case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial cell spacing</td>
<td>(\Delta x)</td>
<td>100 km</td>
</tr>
<tr>
<td>Coastal points spacing</td>
<td>(\Delta x_{\text{coast}})</td>
<td>25 km</td>
</tr>
<tr>
<td>No. of neighbors</td>
<td>(N_{\text{neibs}})</td>
<td>20</td>
</tr>
<tr>
<td>SPH length scale</td>
<td>(L)</td>
<td>150 km</td>
</tr>
<tr>
<td>Smoothing scale</td>
<td>(L_{\text{smth}})</td>
<td>100 km</td>
</tr>
<tr>
<td>Geostrophic wind drag coefficient</td>
<td>(C_w)</td>
<td>0.0012</td>
</tr>
<tr>
<td>Current drag coefficient</td>
<td>(C_d)</td>
<td>0.0055</td>
</tr>
<tr>
<td>Wind stress turning angle</td>
<td>(\alpha)</td>
<td>30°</td>
</tr>
<tr>
<td>Water stress turning angle</td>
<td>(\beta)</td>
<td>25°</td>
</tr>
<tr>
<td>New ice thickness</td>
<td>(h_{\text{o}})</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Coastal force length scale</td>
<td>(L_{\text{coast}})</td>
<td>25 km</td>
</tr>
<tr>
<td>Coastal force strength</td>
<td>(F_{\text{coast}})</td>
<td>0.1 N m(^{-2})</td>
</tr>
<tr>
<td>Ice strength constant</td>
<td>(P^*)</td>
<td>5000 N m(^{-2})</td>
</tr>
<tr>
<td>Yield ellipse aspect ratio</td>
<td>(e)</td>
<td>2</td>
</tr>
<tr>
<td>Full time step</td>
<td>(\Delta t)</td>
<td>0.5 day</td>
</tr>
<tr>
<td>Position tolerance</td>
<td>(e_{\text{pos}})</td>
<td>25 m</td>
</tr>
<tr>
<td>Velocity tolerance</td>
<td>(e_{\text{vel}})</td>
<td>0.0001 m s(^{-1})</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Schematic of the four-point determination of the internal ice stress gradient. The four points are each 25 km from the cell. The thickness \(h\), the compactness \(A\), and the components of the velocity strain tensor are determined with the SPH formalism at each point. The internal stress tensor \(\sigma\) is then determined for each of the four points, and the spatial gradients in \(\sigma\) are determined with finite differences.
This rheology produced the most realistic simulations when compared with a cavitating-fluid rheology, a compressible Newtonian fluid, and a simple free drift approach.

c. Coastal force

In principle, the coastal points defined above should be sufficient to contain the ice, but inaccuracies in the SPH gradient estimates at the edge of the domain cause cells to occasionally pass between the coastal points. Often these are areas where the coastline is irregular on a scale smaller than the SPH length scale. An ad hoc solution is to create a repulsive force originating from the coastline. This force is given a $1/R^2$ form, where $R$ is the distance between a cell and the coastline and the strength of this force is $0.1 \text{ N m}^{-2}$ at a distance of 25 km. This approach is similar to the normal and tangential forces constructed by Gutfraind and Savage (1997a).

d. Nearest neighbors

In principle, the summations in (4) and (5) should include all of the cells in the model because the integral in (1) covers the entire area. In practice, the cells more than one or two length scales away from the point of interest have little impact because of the Gaussian decay of the weighting function. In order to improve the numerical efficiency, the summation was performed only on the nearest neighbors of a cell. Experiments showed that as few as $N_{\text{min}} = 20$ were needed to produce good results. Figure 3 shows a sample cell and nearest neighbors marked, including the coastal points, as well as a circle showing the distance of one length scale. The nearest neighbors for each cell were determined once a day.

e. Time stepping

The momentum equations are integrated in time using the fifth-order Runge-Kutta-Fehlberg method with an adaptive time step, as in the FORTRAN code RKF45 (Fehlberg 1969). It adjusts the integration step size dynamically to achieve the required level of accuracy. The variables in the integration are the two components of the positions of all the ice cells and the two components of their velocities, $(x, y, u, v)$. For these simulations the tolerance in the positions was set at 25 m and in the velocity at 0.0001 m s$^{-1}$. The model uses a full step size of 0.5 day. This full time step is divided dynamically into 100–2000 small steps for integrating the position and velocity. The area, ice concentration, and mean ice thickness are also determined each small time step from the computed divergence. Typical step sizes are 100–1000 s, and each small step requires six evaluations of the time derivatives $d(x, y, u, v)/dt$.

f. Time derivatives and the momentum equation

The time derivatives of $(x, y, u, v)$ are

$$\frac{dx}{dt} = \dot{x}, \quad \frac{dy}{dt} = \dot{y}, \quad \frac{du}{dt} = f(u) + \frac{1}{\rho} \left( \tau_{xx} + \tau_{yy} + \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + f_{\text{coast}} \right), \quad \text{(8)}$$

and

$$\frac{dv}{dt} = -f(u) + \frac{1}{\rho} \left( \tau_{ux} + \tau_{uy} + \frac{\partial \sigma_{ux}}{\partial y} + \frac{\partial \sigma_{uy}}{\partial x} + f_{\text{coast}} \right), \quad \text{(9)}$$

where $\dot{x}$ and $\dot{y}$ are the SPH smooths of the velocity field, $f$ is the Coriolis parameter, $\tau_x$ and $\tau_y$ are the air and water stresses, $\sigma$ is the internal ice stress tensor, $f_{\text{coast}}$ is the normal coastal force, and $\rho$ is the density of ice.

g. Velocity smoothing

In order to maintain numerical stability in the model near the boundaries we found it necessary to apply an SPH smooth to the velocity once each full time step. A smoothing length of 100 km was used. Because the smoothing includes the stationary coastal points, the speed of the cells near the coast is reduced in the process. The thickness and compactness are also smoothed to ensure smooth fields; however, the coastal points are not included for these variables.

Changes in the thickness and the compactness are
computed following the procedures outlined in Hibler (1979). These equations are based on the divergence computed from the SPH-determined strain rates and on the ice growth rates for open water and for the thick ice. The ice growth table of Thorndike et al. (1975) provides the seasonal and thickness-dependent growth rates. The equations for the time derivatives in a Lagrangian framework are

\[ \frac{dh}{dt} = -h \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + S_h \quad \text{and} \quad (10) \]

\[ \frac{dA}{dt} = -A \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + S_A, \quad (11) \]

where \( h > 0 \) and \( 0 < A < 1 \) and \( S_h \) and \( S_A \) are thermodynamic terms given by

\[ S_h = f \left( \frac{h}{A} \right) A + f(0)(1 - A) \quad \text{and} \quad (12) \]

\[ S_A = \max \left[ f(0) \left( \frac{1 - A}{h_0} \right), 0 \right] + \min \left( \frac{S_A A}{2h}, 0 \right), \quad (13) \]

where \( h_0 \) is a fixed demarcation between thick and thin ice, 0.5 m.

**h. Forcings**

The geostrophic wind is derived from the International Arctic Buoy Program (IABP) pressure fields. The monthly mean ocean currents are obtained from the output of an Eulerian fully coupled ice–ocean model (Zhang and Rothrock 2000) with a grid cell size of 40 km. The currents are the climatological mean for the period 1979–93. Using mean currents instead of daily varying currents will cause some additional error in the simulated ice motion. The winds and currents are linearly interpolated to cell locations. The initial mean ice thickness was taken from the mean ice thickness of the Eulerian model for the January of the initial year of a simulation.

**3. Model results**

Two samples of the model output are shown in Figs. 4 and 5. Figure 4 shows the trajectories of all of the cells over a 10-day period. Strong variations in the shapes of the trajectories are seen from one region to another, yet locally the trajectories show a great deal of coherence, reflecting the imposed smoothness of the velocity field. The ice is almost stopped north of Greenland as a result of the internal ice stress in the thick ice found in this region. The ice is thickest near the Canadian archipelago, reflecting the initial ice thickness field. The
model trajectories show moderately good correspondence with the buoy trajectories. In Fig. 5 the trajectories are shown for a 30-day period and the mean model ice velocity is interpolated to a regular grid. Interpolation to a regular grid may often be necessary in future applications of the model and is easily accomplished with (2).

a. Validation and sensitivity tests

Buoys deployed on the ice by the IABP provide an excellent source of validation for model estimates of the ice velocity. Buoy velocities are derived from daily buoy positions as determined by the Argos satellite system, with position errors less than 300 m. Although the same buoys provide pressure data for the model forcing fields, the errors in the pressure transducers are not related to the errors in the buoy positions. A series of sensitivity tests were run to determine the best value to use for some of the model parameters with the buoy velocities providing the validation data. The test period was the year 1998, with the initial conditions provided by a 1-yr integration through 1997. Comparisons were made of the daily buoy velocity with the daily averaged model velocity interpolated to the buoy positions using the SPH interpolation procedure with a length scale of 100 km.

The mean speeds, the rms vector difference in the velocities, the turning angles, and the vector correlations of the velocities were determined. The rms difference is found from the magnitudes of the vector differences between the model and the buoy

\[ \text{RMSD} = \sqrt{\frac{1}{N} \sum |U_{\text{model}} - U_{\text{buoy}}|^2}, \]  

where the model and buoy velocities, \( U_{\text{model}} \) and \( U_{\text{buoy}} \), are expressed as complex numbers; \( N \) is the number of pairs. The squared correlation coefficient \( R^2 \) is found by a least squares fit of the equation

\[ U_{\text{model}} = U_{\text{buoy}} A e^{i\theta} + D + \epsilon. \]

The real numbers \( A \) and \( \theta \) give the magnitude scaling and the angle bias, respectively. Here \( D \) is an additive constant vector and \( \epsilon \) is the error of the fit. The squared correlation \( R^2 \) is the fraction of the variance of \( U_{\text{model}} \) explained by the first two terms on the right hand side of (15). The angle bias is given by \( \theta \) and the speed bias by \( N^{-1} \sum (|U_{\text{model}}| - |U_{\text{buoy}}|) \). In order to account for spatial and temporal variability in the regression coefficients, we have followed Thomas (1999) and binned the observations into a 160-km grid and 1-month intervals. Velocities from grid squares and months with 10 or more buoy observations were then fit with (15) to determine the squared correlation. The median values of \( R^2 \) for all such fits are reported in the Tables 2 and 3.
The parameters examined fall into two groups. One group consists of model numerical parameters (Table 2) and includes the length scale for the SPH strain-rate calculations, the number of neighbors included in the SPH calculations, the velocity tolerance, and the smoothing length scale. The second group consists of physical parameters (Table 3) and includes the air drag coefficient, the air stress turning angle, the ice strength, and the yield ellipse aspect ratio. Our values for a 1-yr comparison show rms differences to be 0.062 m s\(^{-1}\) for the standard case and the correlation coefficient for the year to be \(R = 0.798, R^2 = 0.637\).

b. Numerical parameters

The numerical-parameters sensitivity tests show that the simulations are not very sensitive to the values of the parameters. Rms differences range only between 0.061 and 0.064 m s\(^{-1}\), and the squared correlation coefficient ranges only from 0.626 to 0.638. The speed bias and the turning angle bias also do not change significantly. A larger length scale improves the correlation slightly but can smooth the velocity field excessively if it is too large. The model–buoy comparison is also surprisingly insensitive to the number of nearest neighbors used to determine the strain rates or to the velocity tolerance used to guide the adaptive time stepping. The time stepping is largely controlled by cells where the accelerations are large and these cells are typically located very near the coasts, where few buoys are deployed. More accurate solutions near the coasts (obtained with reduced error tolerances in the adaptive time stepping) are not reflected in improved performance statistics measured at the buoys, which are found mostly in the interior. The velocity smoothing scale also does not help the performance statistics. However if no smoothing is used, time series plots of the velocity of individual cells occasionally indicate unrealistic oscillatory behavior. The SPH interpolation procedure for estimating the model velocity at the locations of the buoys effectively smooths these oscillations among adjacent cells and the interpolated model velocity matches the buoy velocities quite well. However, to avoid these oscillatory instabilities we think it best to include a small amount of smoothing of the velocity fields so as to insure that the assumption of a smoothly varying velocity field is accurate.

c. Physical parameters

The sensitivity tests for the physical parameters (Table 3) show that the magnitude of the speed bias is most sensitive to the air drag coefficient and is at a minimum (2.1\%) for \(C_w = 0.0012\). This value implies a ratio of \(C_s/C_w = 0.22\), lower than the range of 0.38–0.60 found by Kreyshcer et al. (2000). This lower value is likely related to the lower value of the ice strength \(P^*\) that we use, 5000 N m\(^{-2}\) as compared with 15 000–30 000 N m\(^{-2}\) used in their study. While the bias is a minimum at \(C_s = 0.0012\), the rms difference is slightly lower for \(C_s = 0.0006\). The angle bias is most sensitive, of course, to the turning angle \(\alpha\) for the wind stress. Because of the free parameters in the linear model used to compute the correlation, the correlation is insensitive to changes
in either of these two parameters. The ice strength $P^*$ and the aspect ratio of the yield ellipse have a limited impact on the velocity comparisons over the ranges tested. However, the speed is reduced as the ice strength is increased. Perhaps most surprising in these tests is the insensitivity of the model simulations to changes in the key parameters. The model speed bias and turning angle bias respond as expected, but the rms differences and the correlations do not change greatly within the testing range of the parameters.

Some model parameters have significant impacts on the computation times for the model. The computation time for the standard case is about 5 h yr$^{-1}$ on a 2-GHz workstation [the model is implemented in the Interactive Data Language (IDL)]. The model is much slower if the length scale $L$ is small, taking three times longer for $L = 100$ km than for $L = 300$ km. The greater smoothing used to determine the strain rates reduces the size of the coastal accelerations and hence reduces the requirements for small time steps in the adaptive-time-stepping procedure. The computation time is also sensitive to the number of neighbors used in the SPH strain-rate calculations and increases linearly with $N_{neibs}$. It takes about 2.5 times as long to compute with 30 neighbors than with 10. The ice strength $P^*$ also influences the computation time. It takes about 50% longer to integrate 1 yr if $P^*$ is 10 000 N m$^{-2}$ instead of 2500 N m$^{-2}$ because of the larger accelerations found with the stronger ice.

Finding optimum physical parameters for a numerical ice model depends heavily on the forcing data used and the time interval examined. Here a 1-yr simulation is used; a longer period of analysis with more realistic thermal forcing and ocean current forcing would be preferable for establishing optimum model parameters. These tests indicate ranges of values that will likely need to be examined in a more complete analysis.

d. A 5-yr integration

We performed a 5-yr integration of the model for the years 1993 through 1997. The model simulations are compared to the buoy velocities at the locations shown in Fig. 6. Note that there are few buoys near the coasts and almost none in the Chukchi, East Siberian, and Laptev Seas. These regions may have substantially different internal stresses and ice motion than in the center of the basin, and so the comparisons are less certain for these regions. Time series of the comparisons for a moving 30-day window are shown in Fig. 7. The speed bias ($0.018$ m s$^{-1}$ in winter, $-0.009$ m s$^{-1}$ in summer; $N = 28$ 239 and 14 314, respectively) shows a distinct seasonal cycle with model speeds higher than those of the buoys in the winter. This suggests that a seasonally varying drag coefficient such as that of Ip (1993) or Overland and Colony (1994), both of which have lower values in the winter when the atmospheric stratification is large, would help reduce the seasonal variation. The rms differences, however, are not strongly dependent on the season ($0.072$ m s$^{-1}$ in winter, $0.071$ m s$^{-1}$ in summer). The correlations (not shown) are also not strongly de-
dependent on the season \( R = 0.775 \) in winter, \( 0.767 \) in summer. The mean thickness shows the expected annual cycle and an initial drift to lower values for the first half of the period followed by a more stable equilibrium in the second half. The crude thermodynamic component of the model, represented by a simple lookup table, is not expected to accurately recreate the thickness variability of the ice pack. The thickness does impact the velocity by its influence over the ice strength and some of the errors in the velocity field may be a result of errors in the thickness field. For the entire 5-yr period the correlation coefficient is \( R = 0.76 \), the mean speed bias is \( +0.009 \text{ m s}^{-1} \), and the mean angle bias is \( 8.0^\circ \).

The rms differences and the correlation values for the Lagrangian model are comparable to those obtained with a state-of-the-art Eulerian model. Zhang et al. (2003) simulated the ice motion and growth in a coupled ice–ocean model with a grid resolution of 40 km and with the same forcing wind fields. They found the rms differences between the ice velocity and the buoy velocities to be \( 0.070 \text{ m s}^{-1} \) in both winter and summer over the same 5-yr period and the correlation coefficients to be \( R = 0.66 \) in winter and \( R = 0.74 \) in summer. Their mean model speeds were a little lower (bias = \(-0.026 \text{ m s}^{-1} \) in winter, \(-0.014 \text{ m s}^{-1} \) in summer) reflecting different choices for the drag coefficients.

e. Geostrophic wind relationships

The ice motion in the Arctic Ocean is well correlated with the geostrophic wind speed (Thorndike and Colony 1982; Thomas 1999). Thomas (1999) found that the median vector correlation of the geostrophic wind with the ice motion (as measured by buoys) is \( R^2 = 0.71 \) in the winter and \( 0.73 \) in the summer and autumn. His analysis was for the 15-yr period from 1979 through 1993, and he had removed the spatial and seasonal variability of the linear relation (15) by binning the data into 160-km squares for each month of the year, similar to what we did for the sensitivity tests. He also found that the rms error of eight different formulations of a standard Eulerian model was larger than that found from the linear least squares model. He found that for the Arctic Ocean the buoy mean field had an error of \( 0.085 \text{ m s}^{-1} \) (the standard deviation), the linear model an error of \( 0.052 \text{ m s}^{-1} \), and the Eulerian model errors ranged from \( 0.061 \) to \( 0.089 \text{ m s}^{-1} \). The current model has an rms error of \( 0.074 \text{ m s}^{-1} \) for the 5-yr simulation.

We compared the buoy, wind, and model velocities with separate fits for each 160-km square grid cell and for each month. The median values of \( R^2 \) and the errors in the fit were examined. The geostrophic wind for the 5-yr simulation is slightly better correlated \( R^2 = 0.70 \) with the buoy velocities than the model is \( R^2 = 0.68 \). The model velocities are more correlated with the geostrophic wind \( R^2 = 0.88 \) than the buoy velocities are, in part because any error in the wind field is also reflected in the model response. The rms difference between the model velocity and the buoy velocity is \( 0.065 \text{ m s}^{-1} \), much more than that of the linear model, \( 0.042 \text{ m s}^{-1} \). The fact that the model ice velocity error is larger than that of the best-fit least squares model is not too surprising because the best-fit model has the luxury of choosing a different set of coefficients for every location and month, coefficients that minimize the error by design.

4. Summary and conclusions

The Lagrangian model presented here offers a new way to think about ice dynamics and ice processes. Instead of dividing the world into squares and attempting to keep track of the net flux of ice or momentum into and out of the squares (the classic Eulerian model), we attempt to follow the evolution of particular parcels of ice and model explicitly the forces that impinge on the parcel and the resulting parcel velocities and trajectories. This is a different approach and has required some innovation. In constructing an entirely new model we have become more aware than ever of the creative efforts needed to meld the physical laws of nature with a model framework that is logically and numerically tractable. By necessity, compromises were made, and those presented here are undoubtedly not the last word on the formulation of a Lagrangian dynamic sea ice model.

The most important attribute of the model is that it represents the ice pack with a set of mobile ice cells, each of which is characterized by position, velocity, mean thickness, and compactness. The velocity, thickness, and compactness are thought to vary smoothly in space. The equations of motion that are solved for each cell include terms for the water and air stresses, the Coriolis force, and internal ice stress gradients. The ice stress gradients are found from a viscous–plastic rheology with an elliptic yield curve. The strain rates are found from a weighted sum of the velocities of 20 neighboring cells using the formalism of smoothed particle hydrodynamics. Ice growth and melt rates are determined from a lookup table that depends on season and thickness.

The model performs stably with the adaptive-time-stepping procedure, which changes the size of the integration step size in order to keep the integration error below a set tolerance. This procedure allows the model to take as few as 200 or as many as 5000 steps in a half-day period. The model ice velocity errors are not very sensitive to large changes in both numerical and physical model parameters.

a. Future work

This is a new ice dynamics model that can be refined before it is widely applied. The coastal boundary force could be modified to better allow for the possibility of fast ice. This would entail the formulation of a coastal
force that allows for tensile strength. The number density of the cells could vary spatially by defining regions where the initial cell separation is smaller than found in the bulk of the basin, places of special interest such as in constricted regions, and shelf regions, or in marginal ice zones. The length scale is currently constant but it could be made to vary depending on the number density of the cells so that better spatial resolution of the velocity field could be obtained in regions with a high density of cells.

The thermodynamic growth and melt rates could be modeled using air temperature, wind speed, and short- and longwave radiative flux fields. The focus of this first study is on the Lagrangian dynamic model, so the thermodynamics have been subsumed into a simple seasonal- and thickness-dependent ice-growth table. Along with the thermodynamics, a more physically realistic ridging and redistribution model could be included. The puck-ice model of Lindsay (2003) includes both a thermodynamic and an ice redistribution model and is designed to be used in a Lagrangian context.

b. Data assimilation

One of the prime motivations for designing this model has been to assimilate integral Lagrangian measures of the ice motion, such as from buoys or from the Radarsat Geophysical Processor System (RGPS; Kwok 1998). The RGPS provides measures of the ice motion for a large number of points with temporal intervals from 1 to 10 days. The cells of our Lagrangian model could be associated with particular RGPS trajectories. The model would provide the velocity estimates for intermediate times between the RGPS observations so that the velocity and deformation fields measured by the RGPS might be translated into regularly gridded fields, more easily used for Eulerian model validation or assimilation. Other potential applications of a model such as this are for long-range trajectory analysis (such as of ice production regions or for entrained-minerals tracing experiments), ice mixing (horizontal diffusion) studies, stress propagation analysis, ice rheology studies, or marginal ice zone prediction.

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