MODELLING THE EVOLUTION OF DRAFT DISTRIBUTION IN THE SEA ICE PACK OF THE BEAUFORT SEA

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ABSTRACT

Multi-category re-distribution models are largely untested against observations of the evolving thickness of pack ice on daily or seasonal time scales. To ascertain the accuracy of re-distribution algorithms, a coastal, local sea-ice draft evolution model was developed. The model is initialized with ice draft and velocity data and forced with meteorological data during specific ice motion events. A comparison of modelled and observed thermal development of the sea ice pack draft characteristics through the fall freeze-up season shows excellent agreement indicating thermal growth processes are represented correctly. Modelled ice draft evolution under mechanical forcing forms too much ridged ice under traditional mechanical redistribution schemes.

MOTIVATION

The pack ice of the Arctic Ocean has a great influence on the global climate and yet this region is one of the most sensitive to climate change with complex and indirect responses of the ice cover to global warming (Melling, 2002). To understand the impacts of global climate change, accurate predictions of the Arctic atmosphere-ice-ocean system are needed. Multi-thickness category re-distribution models are one type of model commonly used to predict the evolution of the ice cover in the Arctic (i.e. Thorndike et al., 1975). These differ from models which track the mean thickness of ice types (Gray and Killworth, 1996; Shinohara, 1990; and Haapala, 2000) in that the actual pack distribution is evolved with time allowing comparison with actual ice draft distributions. These models generate average distributions that resemble observed draft data (Flato and Hibler, 1995). However the lack of temporal coverage in draft records in the Arctic does not allow for careful tests of model accuracy. Indeed, ice thickness distributions predicted from the multi-thickness models show greatly varying results between models (Proshutinsky et al., 2001), which suggests the processes that create and maintain the Arctic pack ice may not be fully understood. Models often maintain too much of the thickest sea ice (Flato and Hibler, 1995) leading to overestimates of ice draft. Without validating the re-distribution models against appropriate data, the ability of the models to correctly respond to climate forcing is unknown.

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Continuous sea ice draft observations from moored sonar devices provide the opportunity to model pack ice evolution under specific forcing events. Ice draft evolution is predicted on an hourly scale from observed ice draft (Figure 1) forced with local meteorological data and pack-ice deformation rate observed at a scale of order 50km. The predicted evolution is then compared with observed final draft distributions after intervals of weeks. By using a local short-term model, we can directly compare the model results to the observed draft distribution.

**THICKNESS RE-DISTRIBUTION MODELS**

The re-distribution model used is adapted from the multi-thickness models first suggested by Thorndike et al. (1975). A matrix notation similar to that of Thorndike (1992) was chosen for simplicity. The change in time (\(\Delta t\)) in the draft probability density distribution \(G^t(h)\) is given as:

\[
G^{t+\Delta t} - G^t = (A + F(h,t) + \Psi)G^t + B\Delta t
\]

(1)

where \(F\) is a thermal evolution matrix and \(\Psi\) is a mechanical re-distribution matrix applied to the vector \(G^t\). Matrix \(A\) and vector \(B\) conserve area and volume under divergence.

![Figure 1: Example of the evolving draft distribution of sea ice subject to thermal forcing only over seven days in January 1992, as seen in the site three sonar data. The original observed distribution is shown in the bar graph. Each bar represents a draft thickness bin. Approximately seven days later, the new distribution is shown as a line plot. The thermal growth of both level ice peaks originally at 0.6 m and 1.2 m draft is visible.](image)

Driving the thermal sea ice growth is an estimated sea ice growth rate \(f(h)\). Here \(f(h)\) is calculated using the ice growth model developed by Cavalieri and Martin (1994) that was successfully adapted and applied to the observed increase in modal ice draft in the Beaufort in winter 1991 by Melling and Riedel (1996). These growth rate predictions are forced by atmospheric data observed on the coast at Tuktoyaktuk, Northwest Territories and available from the Canadian Climate Centre, Environment Canada. The growth rate is implemented using the remapping scheme of Lipscomb (2001).
INPUT ICE DRAFT DATA
The Beaufort Sea (Figure 2) is an excellent location for studies of the redistribution of coastal sea ice. Normal circulation in the region is anti-cyclonic and the sea is bounded by land and land fast ice to the south and east. In average years, the sea is covered with first and multi year ice except for August and September when marginal seas offshore become ice free due to easterly winds in early summer (Melling and Riedel, 1996b). Under these conditions, freezing of the sea surface in October produces a widespread population of new level ice. The subsequent continued growth of this ice and its utilization in the formation of new ridges provide annual natural experiments in ice draft re-distribution from “scratch”.

Ice draft and movement data are available from mooring sites throughout the Beaufort Sea over an eleven-year period. Data used in model simulations (Figure 2) are from winter 1991 and a full discussion of the challenges in interpreting these data can be found in Melling and Riedel (1996) and Melling (1998). Note that while the model represents the ice pack in a Lagrangian sense as an evolution of a distribution, draft data are Eulerian in nature.

The study site provides regular events that are suitable for use in the re-distribution model. Along with the general anti-cyclonic circulation, there exist periods of motion convergent upon and divergent from the coast, which can bring a parcel of ice back to the same perpendicular distance from the land fast ice edge. Assuming alongshore homogeneity, the ice seen at the mooring at the end of one of these convergent-divergent events can be assumed to have begun with the initial draft distribution as the ice seen by the sonar at the beginning of such an event. The assumption of alongshore homogeneity is supported by the ice charts from the region which often show symmetrical ice coverage in a line parallel to the land fast ice and allows for the comparison of model and observed conditions.

COMPUTATIONS OF THERMAL EVOLUTION
Recent work (Lipscomb, 2001) has focused on the need for a new thermal growth algorithm that does not display the diffusive qualities (Figure 3) of traditional thermal growth re-distribution methods (the Thorndike/Hibler approach; Thorndike et al., 1975; Thorndike, 1992; Hibler, 1980; and Flato and Hibler, 1995). Lipscomb’s (2001) new remapping algorithm employs an additional tracked mean draft variable to reduce numerical diffusion of the sea ice draft distribution. Comparing the traditional Thorndike/Hibler thermal re-distribution with the thermal remapping in a local re-distribution model run with no mechanical forcing illustrates the effectiveness of the remapping algorithm in reducing diffusion of distribution peaks (Figure 3) over short time scales.

Slight differences in the location of observed and modelled level ice peaks at day 348 do not indicate errors in the thermal growth rates. This difference in level ice draft is due to the comparison of Eulerian draft data with Lagrangian model output. Non-uniform growth of level ice throughout the winter season can be observed in the sonar data indicating that the modal ice passing over the sonar may have been formed under slightly different conditions.
Figure 2: (a) The Beaufort Sea area of the Canadian Basin. Results in this paper are from data collected at site 3 in 1991, which is located north of the land fast ice and the recurring flaw lead at the fast ice edge. (b) Ice motion (1991) is plotted as accumulated displacement. Data used in the model include thermal growth from day 298 to day 318 of 1991 and mechanical re-distribution from day 41 to 69 of 1992 when ice has little offshore net displacement.

Applying the re-distribution model to the 1991 freeze-up season, the model is run from October 9th to November 26th beginning with open water and allowing divergence to continue to generate open water for new ice creation throughout the period. The 9th of October is chosen as the start of the simulation as there were no significant periods of possible ice growth observed in the meteorological forcing data from Tuktoyuktuk before this date. The observed and modelled sea ice draft distributions of November
26th match very closely (Figure 4). A slightly lower draft is observed for some of the level ice in the modelled distribution. This may be due to numerical diffusion or indicate that the thinner level ice is preferentially ridged. The model is run without mechanical forcing to isolate thermal ice evolution and thus the model does not produce the ridged ice signals seen in the observed data at the 1 m draft bin. With confidence that the thermal growth algorithms can produce the observed sea ice draft, mechanical ridging can be incorporated and similarly verified.

Figure 3: Results of the Thorndike/Hibler and Lipscomb thermal re-distribution schemes (Lipscomb, 2001) on the final probability density distribution of sea-ice. (a) Thorndike/Hibler approach. (b) Lipscomb approach.

Figure 4: Modelled draft distribution and observed distributions on November 26th, 1991. Note that the model does an excellent job recreating the level ice depth and shows little excess diffusion. Ice greater than the level ice peak is not present in the model distribution as rafting and ridging of ice was not permitted in this run.
MECHANICAL RE-DISTRIBUTION

The mechanical re-distribution is determined by the convergence rate of ice against the estimated land fast ice edge. Other schemes for re-distribution include estimated stress parameters for sea ice (Flato and Hibler, 1995; Thorndike, 1975). Parameterization of the re-distribution in terms of strain rate allows the model to be driven by observations. The complication of representing stress-strain relationships is avoided. Here, the area lost in convergence is translated directly into a corresponding amount of ridged ice analogous to Thorndike (1992). The land fast ice edge is assumed to be parallel to the coast at a constant distance as estimated from the Canadian Ice Service ice charts. Convergence is then calculated as perpendicular movement towards the fast ice. Level ice is ridged into categories up to the truncated point of 16 h⁻¹, where h is the level ice thickness, as in Flato and Hibler (1995).

The mechanical redistributor, Ψ, contains both a participation function and a transfer coefficient. The participation function determines how much ice should be ridged from the available thickness categories to account for the observed strain rates. In Figure 5, the participation function of Hibler (1980) is used; similar results are obtained when using a linear participation function where the tendency for ice to ridge is assumed to have a inverse linear dependence on thickness.

![probability density plot](image-url)

Figure 5: Modelled sea ice draft (solid) and observed sea ice draft (dashed) can be compared at day 69 of 1992. Model was initialized with the observed draft distribution of day 41. Ridged ice transfer coefficient in this model is linear, creating ridges of all possible drafts. Note that the model generates too much open water (visible in (b) linear plot) and places too much ice into the highest draft categories (visible in (a) log plot).
The transfer coefficient controls the placement of level ice into ridged ice through mechanical deformation. The traditional constant transfer coefficient places ice into a single ridge of maximum allowed draft (Flato and Hibler, 1995; Thorndike, 1975). Using this constant transfer, too much ice is placed in the larger draft categories. In an attempt to find a more accurate ridged ice distribution, additional transfer coefficients were tested. Modelled distributions with linear (assume ridges of any height equally likely to form) transfer coefficients (Figure 5) again show only slightly excessive ice being placed into large draft categories and, by conservation of area and volume, excessive open water formation.

FUTURE DIRECTIONS
Future work will examine the shortcomings of the mechanical redistribution model. The excessive ridged ice produced by the mechanical redistributor is likely due to the inapplicability of the transfer coefficient. Conceptually, at the start of ridging, ice should not be able to form ridges of maximum height; particle simulations by Hopkins (1998) indicate that maximum height is reached only after a period of ridge building occurs. The inclusion of a tracked variable to monitor the length of time that convergence has been occurring is suggested. Such a variable would be analogous to the mean draft tracked for thermal remapping (Lipscomb, 2001). Future work will attempt to develop a mechanical re-distributor that includes a recent time history of convergent forcing.

Excessive ridged ice in large draft bins was observed in Flato and Hibler (1995), although visible to a lesser degree. This is due to larger time steps where the assumption of a ridge of maximum height forming instantly is less likely to introduce over-ridging. The lack of accurate ablation in most models (Flato and Hibler, 1995) could also influence the excessive amounts of ridged ice created by re-distribution models. A local model is well suited to addressing this concern, as it can be run over smaller time scales focusing only on the melting of ice draft, and use observed data as an initial condition. In this case, excessive draft from mechanical ridging can be eliminated from the model and thermal melt processes isolated.

With accurate thermal and mechanical redistributors identified, the model can then be applied to other annual data sets and in different seasons. The thermal evolution model implemented now is not designed to recreate melting events correctly. The extension of the model to handle a full season of ice evolution will allow us to study annual cycles. On a local scale, this model may be used to make predictions of the effects of climate change through changes oceanic heat, meteorological variables, and ice pack strain rates on the locally generated sea ice distribution in the Beaufort. On a larger scale, it is expected that the results of the local model will help to explain the nature of the processes controlling sea ice draft and how to best implement them in global and basin scale models.

REFERENCES


