OPERATIONAL MODELING OF THE AUTUMN ICE ADVANCE IN THE BARENTS SEA

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ABSTRACT
A new marginal ice zone (MIZ) model is under development for use at the National Ice Center (NIC) in Washington, DC as a tool to aid expert ice analysts in the production of operational ice charts. The model thermodynamics are driven by daily ice concentration retrievals from passive microwave data from the Special Sensor Microwave Imager (SSM/I). Validation of the model for the autumn, 2001 ice advance in the Barents Sea was performed by comparison with a series of Radarsat synthetic aperture radar (SAR) images and field observations obtained aboard the USCGC Healy in the Barents Sea in October, 2001. The model is shown to perform very well — episodes of new ice growth are well detected and predicted concentrations of new and young ice typically match observations to within the accuracy of the SAR interpretation. The model is shown to produce the observed ice conditions in late October more accurately than the NIC ice chart produced from the same SAR data.

INTRODUCTION
The NIC produces bi-weekly charts of global sea ice conditions using a variety of satellite data sources, the interpretation of which relies on visual analysis by expert ice analysts. Under cloudy conditions, analysts rely heavily on Radarsat SAR data. In the marginal ice zone, this analysis can be difficult because of the variability of the ice cover, its high degree of inhomogeneity, and the small size of individual floes (Garcia et. al., 2002). An operational model that can reliably track ice motion and predict the growth and development of the various types of ice of interest to the NIC can therefore be a valuable aid to the analyst.

Unfortunately, current operational sea ice models are not very reliable in the MIZ (Van Woert, et. al., 2002). This is largely due to inaccuracies in the forcing data and lack of appropriate model initialization. While such difficulties may be less of an issue with long term climate studies, they are often critical for operational ice analysis in the MIZ where ice conditions can change rapidly and we are interested in time scales of a day to several weeks. Here we present the results of a model validation for the Barents Sea of a

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new operational MIZ model developed for the NIC that attempts to overcome these difficulties through the assimilation of satellite data.

**THE MODEL**

The model is a frazil/pancake growth model that was initially developed for use in the Greenland Sea (Toudal and Coon, 2001). Rather than compute new ice growth through a balance of heat fluxes at the ocean surface, the thermodynamics are driven by daily ice concentration estimates from SSM/I. For each day, the current ice state is advected by the forcing winds, giving a first guess for the following day. This is compared to the SSM/I ice concentration for the following day, with the difference representing growth or melt. New ice is then apportioned between frazil and pancake ice (for details, see Toudal and Coon, submitted manuscript, 2003). Older first-year ice and multiyear ice can be treated as thick pancake ice, as the model makes no prediction of individual floe sizes.

For simplicity, the ice is assumed to be in linear free drift, forced only by the wind. While this ignores much of the true ice dynamics, errors in the wind forcing field and lack of ocean current data suitable for operational use likely have more influence on errors in predicted ice motion than the omission of more complex physical behavior. The wind drag coefficient and turning angle were chosen to best reproduce the observed ice motion during the study period. Wind forcing is provided from the Naval Operational Global Atmospheric Prediction System (NOGAPS) (Hogan and Rosmond, 1991). SSM/I ice concentrations are computed using the NASA Team 2 algorithm (Markus and Cavalieri, 2001).

![Figure 1: Map of the study area. Extent of sea ice on September 1 and November 15, 2001 is shown. Dashed box indicates approximate area for which Radarsat SAR imagery and field observations are available.](image)

**STUDY AREA**

Model validation was carried out for the Barents Sea from September 1 to November 15, 2001. From late September to early November near-daily SAR images were acquired for the northern Barents Sea (see Figure 1). From mid-October to early November, direct observations of ice conditions were made aboard the USCGC Healy. These data were used to aid in the interpretation of the SAR imagery. The ice cover in
the study area was composed of a mixture of ice types. Initially, it was composed almost entirely of multiyear ice. Freeze-up began in late September and progressed rapidly until mid-November. The validity of the model is examined by comparing the modeled distribution of first-year and multiyear ice with that observed in the SAR imagery and its ability to detect new ice growth evident in the imagery.

RESULTS
Detection of Ice Growth Events
The ability of the model to accurately detect ice growth events is an important test for its reliability in an operational setting. If a growth event is limited in spatial extent, errors in the computed ice drift may cause comparatively large errors in the amount of ice grown. Furthermore, frazil ice and new ice are often poorly detected by SSM/I (Eppler, et. al. 1992). The combination of these two effects may cause substantial errors in the amount of new ice grown.

Figure 2: Detection of new ice during a frazil/pancake ice growth episode on October 17–18, 2001. Frazil ice formed on October 17 is poorly detected initially (a), but once pancakes begin to form on October 18 the extent of new ice is captured accurately by the model (b). Contours show simulated frazil ice partial concentration in percent coverage. The regions enclosed by the dotted lines indicate the approximate extent of new ice estimated from the SAR imagery. Contours near Svalbard are due to coastal contamination of the SSM/I retrievals and do not represent new ice formation. Images are approximately 500 km on a side. Radarsat imagery © Canadian Space Agency (2001).

On October 17, an episode of extensive frazil and pancake ice production was observed in the satellite data (Figure 2). By October 18, the ice had consolidated to form an expansive area of pancake ice (and possibly some sheet ice). This event was also observed in the field. Frazil ice was poorly detected by the model (dark region in left hand image in Figure 2), but by the next day, the model predicted frazil concentrations of 30% to 40% over the area of pancake ice. Although it is difficult to estimate ice concentration of frazil and pancake ice in the SAR imagery, it appears that this is still an underestimate of the amount of ice present. This delay in detection and underestimation
is due to the weak passive microwave signal of frazil and thin ice. Nevertheless, the extent of new ice is predicted quite accurately.

Another frazil ice growth event was observed over several days on the east coast of Svalbard in early November. This episode began as an isolated tongue of ice to the south of Nordaustlandet that grew towards the northeast, eventually connecting with the main ice pack. Again, the extent of the ice tongue is simulated well by the model (Figure 3). In this case, the frazil ice was detected better by the model, though it is unclear from the SAR imagery how much of the tongue was actually composed of pancake ice. Model performance in this case is a testament to the ability of the SSM/I to detect new ice since the ice tongue is separated from the main pack and thus unaffected by errors in calculated ice motion. This kind of comparison could be useful to tune the SSM/I ice concentration retrievals based on the expected ice type and improve model predictions.

Figure 3: Frazil/pancake ice growth detected by RADARSAT SAR on November 5, 2001 (region enclosed by dashed line). The extent of frazil ice is predicted accurately by the model. Radarsat image © Canadian Space Agency (2001).

**Ice type prediction**

The ability to discriminate between different ice types (e.g. new, first-year thin, multiyear, etc.) is the most important test of the model, because classification into these categories forms the basis of the NIC ice charts. Here, we test the ability of the model to discriminate between multiyear and first-year ice, as this is the most important distinction and the easiest to verify in the SAR imagery. Simulated partial concentrations of first-year ice were compared to estimates from SAR data for subscenes in the images where visual discrimination of ice types could be easily made, and especially those for which field observations were available for validation. For this comparison, first-year ice is defined to include frazil, pancake, and all first-year sheet ice types. The accuracy of this comparison is dependent on the validity of the SSM/I concentration. Meier et al (2002) has shown that the NASA Team 2 algorithm performed very well during the study period.
Modeled first-year ice partial concentrations compared exceptionally well with the satellite data (Figure 4). For areas of predominantly consolidated sheet ice the partial concentrations matched to within the accuracy of the SAR data interpretation, which is estimated to be 5–10%. For regions of predominantly frazil and young pancake ice, the agreement was not as good, with the model generally underestimating the ice concentration. Again, this is primarily due to the weak passive microwave signature of frazil and young ice types.

Figure 4: Comparison of modeled first year ice partial concentration with Radarsat SAR imagery for selected areas. For sheet ice, the first year ice distribution matched quite well (grouping at left). For regions of frazil and young pancake ice (grouping on right), the match was less accurate.

The effect of errors in computed drift was examined by monitoring the drift of a selected group of ice floes from September 26 to November 5 that covered an area of roughly 3000 km². This region consisted of several vast multiyear floes that were easily tracked over the course of several weeks and large expanses of thin, first-year ice. Field observations made in the region in mid-October indicated roughly equal parts thin first-year and multiyear ice, consistent with the Radarsat data interpretation.

Figure 5: Comparison of modeled first-year ice partial concentration with Radarsat SAR data for a selected region of ice floes tracked over a period of 38 days.
The model ice type distribution matched observations well from September 26 (day 269) until October 20 (day 295) (Figure 5). The observed drift during this period was relatively small. From October 20 onward there were strong northerly winds pushing the ice south and creating net divergence in the area of interest. This allowed new ice growth, hence the increase in the concentration of first-year ice evident in the Radarsat data. This is not captured in the model — the drift is overestimated and so the amount of multiyear ice advected into the area of interest is overestimated, with a concomitant underestimation in the percentage of first-year ice.

**Validation of NIC ice charts**

While the model appears to produce good results when compared with the satellite observations, its usefulness for operational use depends on how well it performs at ice type classification compared with an expert ice analyst. Human analysts will generally outperform models at this task because of their ability to make judgements based on visual clues such as floe shape, gray scale, and texture (Bertoia, 1998) and years of personal experience monitoring the local behavior of ice conditions. The strength of a model, on the other hand, is its ability to continuously track changes in the ice cover over time. In the Barents Sea in October, 2001, ice analysis was complicated by persistent cloudiness, so Radarsat data was the primary data source for constructing the October 29 ice chart. Because of the typically small floe sizes and high degree of inhomogeneity in the ice cover near the ice edge, ice often appeared almost featureless and displayed little tonal contrast in the acquired images (see, for example, Figure 3 and Figure 6), making ice classification difficult.

![Figure 6: Radarsat SAR image on October 28, 2001 with contours of first-year ice partial concentration (percent) overlaid: (a) Model. (b) NIC Ice chart for October 29, 2001. The dotted line is the approximate boundary between first-year and multiyear ice, with multiyear ice predominating on the left side of the scene. Radarsat imagery © Canadian Space Agency (2001).](image-url)

The simulated first-year ice partial concentration for October 28 is seen to match the actual ice type distribution better than the NIC ice chart produced on October 29 (Figure 6). The model predicts that the region of predominantly first-year ice extends approximately 300 km north of the ice edge in the region to the northeast of Svalbard,
while the ice chart indicated only 50–100 km. The primary reason for the apparent error in the ice chart is the paucity of discernable geometric clues from the imagery, and in this case, contradictory indicators from gray-scale levels — multiyear ice may appear to be either lighter or darker than the first year ice, confounding definitive identification. Indeed, observations taken from the USCGC Healy showed that individual floes were often a mixture of first-year and multiyear floes. The boundary between predominantly first-year and multi-year ice (dotted lines in Figure 6) was determined by tracking identifiable floes and features that were near the edge early in the study period through the sequence of images. Based on field observations, this boundary appears to be at approximately the 50 % division between the ice types. In light of this, the agreement with the model shown in figure 6 is remarkable. Since the tracked floes were some distance from the true edge and there may be significant differential motion of the ice near the edge, this boundary should be viewed as approximate. Nevertheless, the difference between the estimated first-year ice extent and that from the ice chart is large enough that we can be confident that the model, at least for this test case, exhibits a more realistic ice type distribution than the ice chart.

CONCLUSION
Validation of a new marginal ice zone sea ice model was carried out for the autumn ice advance in the Barents Sea, 2001 by comparison with satellite SAR imagery. The model was able to detect new ice growth reasonably well, considering the weak passive microwave signature of frazil and thin ice types. The ability of the model in discriminating first-year and multiyear ice types was extremely good, with the model prediction of partial ice concentrations matching the observed values to within the accuracy of the interpretation of the satellite imagery in most cases. The model was found to give a more accurate representation of the ice type distribution than the NIC ice chart for October 28, 2001. The underestimation of first-year ice concentration in the ice chart is attributed to the highly inhomogeneous character of the ice cover and the small floe size near the ice edge. This results in a paucity of visible features typically used by the analyst for ice classification. The strength of the model as an operational tool is in its ability to track ice motion continuously, and hence detect areas of new ice growth. In areas where the imagery is ambiguous, the model could be a valuable aid for routine ice analysis.

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REFERENCES


