Sea Ice Ridge Modelling : A Comparison of Approaches in a Continuum Model

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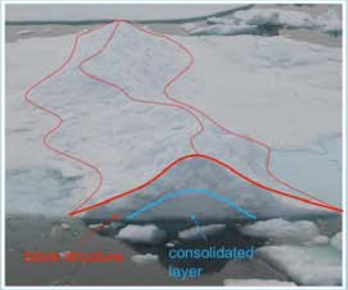
Ice Ridging Information for Decision Making in Shipping Operations

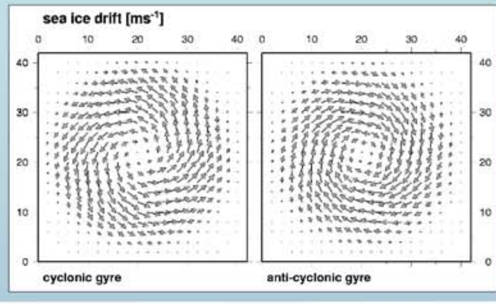
Introduction

Sea ice grows thermodynamically until heat flux from, and conductive heat loss to, the ocean are balanced. In the Arctic this equilibrium thickness reaches 2-3 m. Thicker ice and especially morphological features are the product of dynamic deformation. About 70% of the Arctic sea ice volume evolves from deformation processes. These need to be represented in a dynamical sea ice model in order to cover dynamical growth and lead opening. Due to convergent and shear drift ice floes collide and raft on top of each other or pile up in broken blocks, so-called ridges. Here, three different ways to incorporate ridge build up and development of a deformed ice class into a numerical sea ice model for the Arctic are compared. Ridge density, number of ridges per kilometer along a random profile, is used as variable of comparison.



Model basics

For this study a dynamic model with a viscous-plastic rheology based on the work of Harder (1996) after Hibler (1979) is used. The model includes three ice classes: open water, level and ridged ice. Though model parameters are set for Arctic sea ice, a simple rectangular grid with a 1/4 degree horizontal resolution and a time step of 6 hours are applied, according to the recent Arctic model settings. The thermodynamics, which are normally part of this model, have been turned off and replaced by a simple restoring mechanism in order to reduce the complexity of effects to the ice classes and ridge formation.



Experiments

In order to show the differences of the various ridging algorithms, which are presented below, two basic settings were chosen: a cyclonic and an anti-cyclonic wind pattern. Using parameter settings for the Arctic this leads to a rotation of the ice with a diverging resp. converging component from resp. to the centre of the gyre. Both cases include convergent and shear ice motion, the two sources for ice deformation.

Additionally the disturbing effect of land masses, narrowing the ice drift, has been investigated under the cyclonic wind pattern. Here, two headlands of different size rise into the ice drift current.

Ridge Algorithm 1

This type contains a redistribution function based on the work of Flato and Hibler (1991) and applied by Harder and Lemke (1994). The prognostic equations for level and ridged ice concentration and volume are extended by a redistribution term T_A as sink resp. source:

$$T_A = (\psi_s + \psi_c) e^{-C(1-A)}$$

$$\psi_s = \frac{1}{2}\left(\Delta_\varepsilon - |\dot\varepsilon_{11} + \dot\varepsilon_{22}|\right) \qquad \psi_c = \begin{cases} -(\dot\varepsilon_{11} + \dot\varepsilon_{22}), & \text{if } \operatorname{div}\vec{u} < 0 \\ 0, & \text{else} \end{cases}$$

where $\dot\varepsilon_{xx}$ are components of the strain rate tensor.

The deformed ice volume per time step is used to calculate ridge density. Airborne laser profiles of the sea ice surface, collected during several Arctic expeditions covering the Transpolar Drift Stream from 1995 to 2004, exhibited for all the expeditions a probability density function of exponential shape decreasing to larger sail heights. With this exponential fit for sail heights and assuming also an exponential decrease for ridge link lengths, random ridge volumes are generated until deformed ice volume is used up. Concerning ridge geometry a triangular shape for sails as well as keels is assumed. From the total length of all ridge links the ridge density is derivable after Mock et al. (1972):

$$D = \frac{2L}{\pi A_r}$$

Ridge Algorithm 2

Another possibility to describe ridging is presented by Steiner et al. (1999). In this model a prognostic equation for sea ice surface roughness R has been added. The source of this deformation energy is the work performed by internal forces $P = \dot\varepsilon \cdot \sigma$, the product of strain rate and stress tensor. This deformation energy is then used to develop a relationship for ridge density:

$$D = \frac{1}{16}\sqrt{\frac{R}{h}}$$

where h is the ice volume per area.

Ridge Algorithm 3

Lensu (2003) developed prognostic equations for ridge density D and sail height H. The source terms are based on:

$$\alpha_D = \frac{-\nabla \cdot \vec{u}}{|\varphi_D|} \quad \text{and} \quad \varphi_D = \frac{-315 p_{D,H}}{315 A D p_{D,H} + 1000}\left(1 - 0.081\sqrt{ADH}\right)$$

where A is the ice concentration and p the clustering parameter. The latter describes the reduction of cross-sectional area of the triangular ridge geometry in case ridges are pushed into each other. The equation for p has been derived from ensemble runs with a one dimensional model simulating sea ice surface profiles:

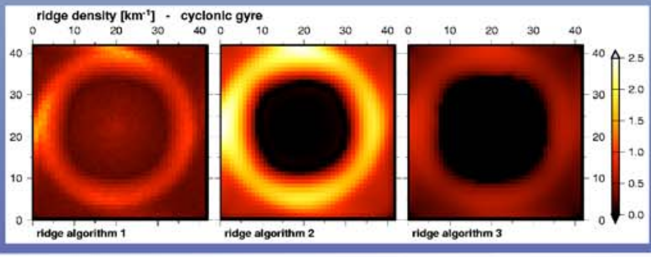
$$p = \min\left(1.24 e^{-0.16\sqrt{ADH}}, 1\right)$$

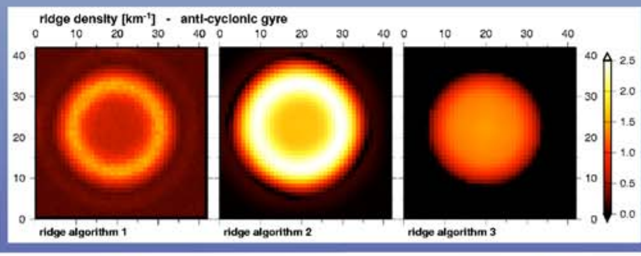
where h_l is the level ice thickness.

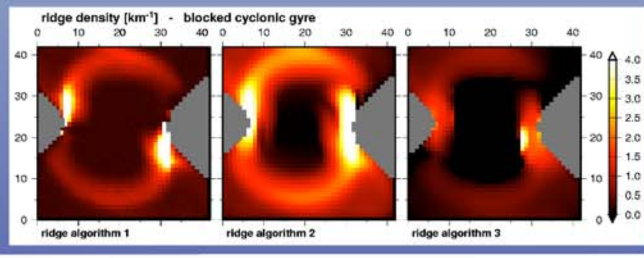
Additionally the one dimensional profile model was used to derive an equation for the mean ridged ice thickness in dependence on D and H:

$$h_{r_{fi}} = 0.3 H e^{(0.5\sqrt{D})}$$

In contrast to ridge algorithms 1 and 2 this one does not account for effects of shear.







Discussion and Conclusions

Three different methods to implement the process of sea ice deformation resp. dynamical ice growth into a numerical sea ice model have been presented. Though at first view the patterns in each experiment are similar, it is obvious that the amplitudes and the dispersion of the ridge density generated by the three algorithms are different:

- highest ridge density develops with deformation energy method and largest dispersion with statistical random generation
- algorithm 1 and 2 tend to a ring structure especially in the anti-cyclonic experiment
- ridge algorithm 3 misses shear effects and is therefore less effective in the unblocked drift experiments
- finally the experiment with blocking land masses shows that with algorithm 1 the area of ridging is very distinct and best pronounced while algorithm 2 tends to develop a smoothed pattern and algorithm 3 ends up in between with again a comparably low ridge density.

These results definitely make a comparison with measured ridge profiles necessary, after the algorithms will have been implemented to an Arctic grid with realistic, varying forcing including thermodynamics.

Another question, after ridge formation, is the melting process during summer months and the transition from first-year to multi-year ice. Due to aging - melting, consolidation and snow accumulation - ridges "disappear" from measuring profiles, when a cut-off height is used.

Literature

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