P1.18

AN IDEALIZED STUDY OF OPEN WATER FORMATION IN SEA ICE

Nadja Lönnroth*[1], Jari Haapala[2] and Achim Stössel[1]
[1] Department of Oceanography, Texas A&M University, USA
[2] Finnish Institute of Marine Research, Helsinki, Finland

1 INTRODUCTION

The amount of open water in sea ice, i.e. leads, cracks and polynyas, around Antarctica has a substantial influence on the formation of Antarctic Bottom Water (AABW). In particular open water enhances the turbulent heat fluxes from the ocean to the atmosphere in fall and winter and as ice is formed in open water areas during freezing, the underlying waters become saltier and thus denser due to brine rejection. This is a primary cause for High Salinity Shelf Water, a major source for AABW (e.g. Orsi et al., 2002).

Coarse resolution global ocean circulation model experiments indicate a strong coupling between AABW formation and local sea ice processes in the Southern Ocean (Goosse and Fichefet, 1999; Stössel et al., 2002). A somewhat open question is the magnitude of the effect of polynyas and leads on the annual ice production. For the Weddell Sea there are some studies on this topic. The coastal polynyas occupy only a small fraction, 0.2%, of the total sea ice area of the Weddell Sea but their effect in total ice production is 2.5-9% (Markus et al., 1998; Renfrew et al., 2002). Concerning leads, there is an estimate that after the development of the first ice cover in the fall the leads contribute over 50% to the total ice formation in the Weddell Sea. Thus, an accurate model representation of open water within a sea ice cover is essential to reducing errors in ice production rates, total energy transfer and brine release (Eisen and Kottmeier, 2000).

In climate models, sea ice is usually described as a single thickness category, which evolves due to thermodynamics and dynamics (Hibler, 1979). However, it is widely known that sea ice is a mixture of different ice thicknesses, and that the thickness distribution on the geophysical scale determines the mechanical and thermodynamical characteristics of the ice pack, as well as the heat and momentum fluxes between the ocean and the atmosphere. Thorndike et al. (1975) presented a theory of sea ice thickness distribution. The first generation of ice thickness distribution models (Hibler, 1980; Flato and Hibler, 1995) were based on straightforward discretization of the thickness distribution function, which tends to yield diffuse solutions if the number of thickness categories is low. The recent developments (Bitz et al., 2001; Haapala, 2000) overcome this problem as those models resolve the evolution of thickness and concentration of discrete ice categories.

A study of open water production in the Arctic (Stern et al., 1995) indicates that models with two categories and no redistribution do not treat open water production properly. They argue that a redistribution term to the ice concentration equation is needed and preferably one more ice class to distinguish open water from thin ice.

We will here compare Hiblers two category ice model to a multicategory model that redistributes ice into ridged and rafted ice during deformation processes, thereby focussing on the impact on the respective open water fraction. Two situations are investigated: 1. The development of a coastal polynya due to offshore winds in a closed basin that is initially ice covered. 2. A low pressure system travelling across a uniform ice field.

2 THE MODEL

The model solves the momentum balance of sea ice with viscous-plastic rheology (Hibler, 1979), and making use of the semi-implicit decoupling of the x and y ice momentum equations following (Zhang and Hibler, 1997). The ice thickness redistribution is solved following Haapala (2000). The evolution equations for ice concentration and thickness state that the local changes of ice concentration and thickness are due to advection, redistribution processes and thermodynamics.

$$DA_i/Dt = \varphi_i^A + \Theta_i^A \quad (1)$$

$$D\tilde{h}_i/Dt = \varphi_i^h + \Theta_i^h \quad (2)$$

*Corresponding author address: Nadja Lönnroth, Univ. of Helsinki, Div. of geophysics, 00014 Helsinki, Finland; email: nadja.lonnroth@helsinki.fi

where A is ice concentration and $\tilde{h}$ is mean ice thickness per unit area, φ is the redistribution term, Θ is the thermodynamic growth or decay rate and i denotes a particular ice category. Redistribution terms determine the mass flux between ice categories and the change of concentrations of ice categories during deformation processes. The decay rates of level ice depend on the shape and porosity of the deformed ice, and the redistribution functions describe that *i)* the velocities have to be converging during deformation *ii)* the rate of deformation depends on the compactness and *iii)* the ice thickness defines the type of deformed ice. The demarcation thickness between ridged and rafted ice creation used here is 17 cm. Thermodynamic effects are described by a simple function where ice thickness growth or decay rate is a function of air temperature and ice thickness.

3 EXPERIMENTS AND RESULTS

For the offshore wind experiment, an idealized closed model domain was constructed with the downwind lateral boundary far enough from the upwind boundary such that the development of the coastal polynya is not affected by the downwind boundary. Three offshore wind scenarios were considered: *i)* constant 20 m/s winds, *ii)* winds varying sinusoidally in time between 15 m/s and 25 m/s with a period of two days but constant in space and *iii)* winds varying sinusoidally in space along the coast between 15 m/s and 25 m/s but constant in time. Initial conditions of ice are 0.5 m thick level ice with 100% concentration. An air temperature of -30°C is specified for the thermodynamic ice growth rate.

The first two cases show no significant difference between the traditional and the multicategory model, as opposed to the third case. Due to the sinusoidal winds, the thickness fields show a wavy pattern (see figures 1a and b), where the thinner ice extends further out in areas with higher wind speeds (at x≈100, 300, 500, 700). A major difference between the two models is the thinner ice zones extending farther north in the multicategory model than in the traditional model. The same holds for the open water fraction (figures 1c and d). The open water fraction reveals two features. The first is more open water along the coast where the winds are strongest. The second is correlated with the sinusoidal pattern that extends half way across the basin, where the largest open water fractions occur in between the wind maxima. The first feature is similar in both models and shows where the ice is pushed away from the shore by the winds. The second one, on the other hand, is related to the ice velocity divergence that is largest along the stripes where the wind is weakest.

When looking at the differences between figures 1 (c and d), we see that the largest differences are located in areas where the wind velocities are at maximum, thus coinciding with the locations of rafted ice (figure 1a). It is found that the maximum difference is 2% (not shown).

In the cyclone experiment, the cyclonic winds were created by an idealized lowpressure, i.e. a circular anomaly, 640 km in diameter, with a minumum of 970 mbar embedded in a constant 1000 mbar pressure field from which the geostrophic winds were calculated. The model domain consists of a rectangular channel 3600 km × 1200 km where the lowpressure system is allowed to propagate along the channel at a rate of 160 km per day. Nonlinear disturbances occur due to the initiation of ice motion from a state of rest upon initialization of the winds at the left end of the channel. After 7.5 days, or at 1200km down the channel, such disturbances have vanished and the results reflect a steady state situation. In this case study, ice thermodynamics have been omitted in order to distinguish the open water produced by dynamics. An f-plane centered at $\phi = 80°N$ has been used, as the β-effect was negligible.

Figure 2 illustrates the ice concentration and velocity for the multicategory and the traditional model after the lowpressure system has travelled 12.5 days. In the region of immediate influence of the cyclonic winds, the ice concentration patterns turn out to be similar. Lower ice concentration occurs in the north-eastern and the south-western sectors of the cyclone. Noticeable differences in the ice concentration pattern occur in the wake of the system, as well as in the south-eastern area of the system. Here, lower ice concentration emerges in the multicategory model. With respect to the wake, the multicategory model reveals two zones of lower ice concentration, whereas only one is visible in the traditional model. The ice thickness patterns (not shown) are a direct reflection of ice redistribution due to ridging and open-water formation. As a result, the ice concentration pattern in figure 2 follows that of ice thickness closely.

4 DISCUSSION AND CONCLUSIONS

The differences in the results of the two models can be explained as follows.

In the offshore wind case, as the polynya opens

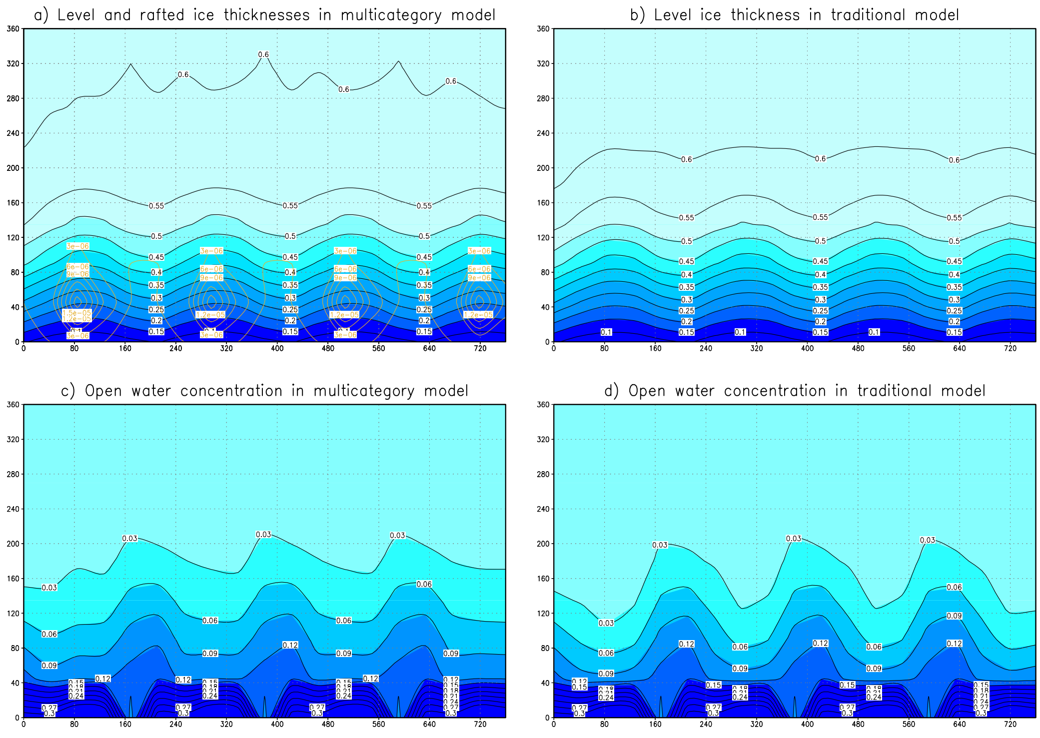

Figure 1: Offshore wind experiment with winds varying sinusoidally in the x-direction.

up, it refreezes immediately due to thermodynamic processes. Newly formed thin ice may break up again under divergence forming new leads, ultimately leading to the sinusoidal shape of the open water concentration. This is simulated in both models. In the mutlicategory model, however, rafted ice is formed where there is convergence (figure 1a). Since ice volume is conserved with respect to dynamics, it is relocated in a manner that more open water is produced (for ex. at x=290 and 500).Thus, a difference in the amount of open water is produced by the two models such that in convergent zones the multicategory model produces a larger open water fraction.

With respect of the cyclone experiment, lot of the behaviour of the ice field can be explained by the divergence of the ice velocity field. Low ice thickness and concentration occurs in the sectors of the cyclone where there is divergence, i.e. in the north-eastern and south-western sectors whereas convergence occurs in the north-western and south-eastern sectors. The differences in the magnitude of divergence are due to the direction of propagation of the cyclone relative to the flow set up by the cyclone.

The fact that divergence and convergence occur in opposite order, i.e. first creation of open water and then ridging in the northern zone, while first ridging and then creation of open water in the southern zone, seems to lead to the asymmetry of the wake. In the second case, thicker ice is created initially in the south-central zone in the multicategory model due to convergence. Since enhanced ice strength has no impact under divergent conditions, however, ice can freely diverge and create open water in the south-western tail end of the cyclone. In the northern zone, on the other hand, where the sequence ends with convergence, the open-water wake is smaller.

The major difference between the two model versions is that the traditional model produces overall less open water. The traditional model does also not yield any thickening in the south-eastern area of the cyclone. Furthermore, while open water (and ridged ice) remains once created in the multicategory model, it largely closes up after the cyclone has passed in the traditional model.

Both the offshore and cyclonic wind cases investigated here indicate that redistribution processes have a noticeable effect on the production of open water in sea ice, especially in situations where the winds vary spatially, giving rise to both divergence and convergence in the ice velocity field. Thus, since the open-water fraction in sea ice has a sub-

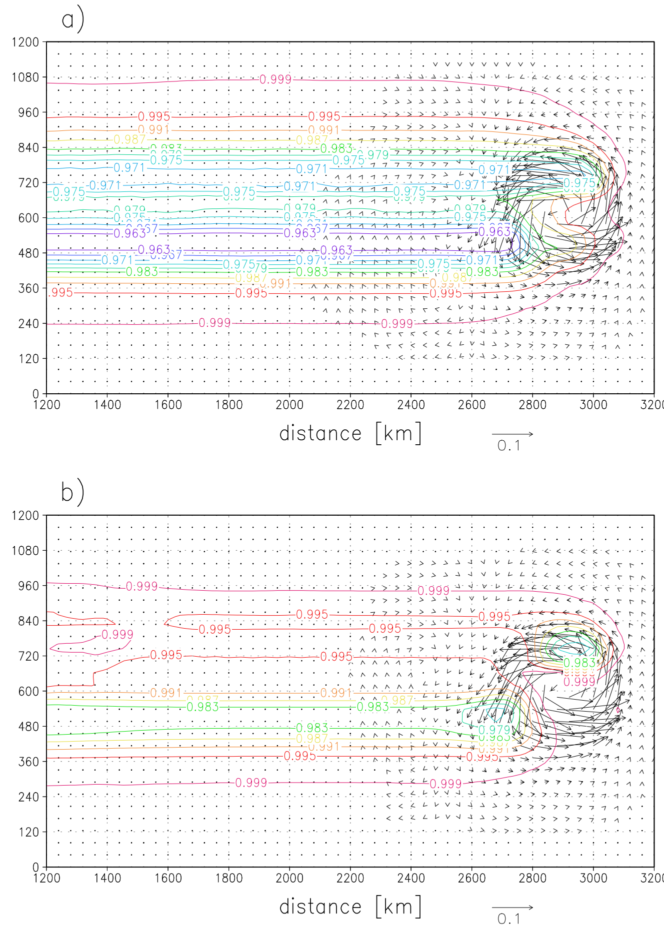

Figure 2: Cyclonic wind experiment: Total ice concentration and ice velocity field as simulated with a) multicategory model and b) traditional model (without redistribution).

stantial effect on deep- and bottom water formation, consideration of redistribution processes in global ocean circulation models seems worth pursuing.

ACKNOWLEDGEMENTS

This research is sponsored through NASA's research grant NAG5-10641.

References

Bitz, C. M., Holland, M. M., Weaver, A. J., and Eby, M. (2001). Simulating the ice-thickness distribution in a coupled climate model. *J. Geophys. Res.*, 106(C2):2441–2463.

Eisen, O. and Kottmeier, C. (2000). On the importance of leads in sea ice to the energy balance and ice formation in the weddel sea. *J. Geophys. Res.*, 105(C6):14045–14060.

Flato, G. M. and Hibler III, W. D. (1995). Ridging and strength in modelling the thickness distribution of arctic sea ice. *J. Geophys. Res.*, 100(C9):18611–18626.

Goosse, H. and Fichefet, T. (1999). Importance of ice-ocean interactions for the global ocean circulation: A model study. *J. Geophys. Res.*, 104(C10):23337–23355.

Haapala, J. (2000). On the modelling of ice-thickness redistribution. *J. Glaciol.*, 46(154):427–437.

Hibler III, W. D. (1979). A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.*, 9(7):815–846.

Hibler III, W. D. (1980). Modelling a variable thickness sea ice cover. *Mon. Wea. Rev.*, 108:1943–1973.

Markus, T., Kottmeier, C., and Fahrbach, E. (1998). Ice formation in coastal polynyas in the weddel sea and their impact on oceanic salinity. In *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, volume 74 of *Antartic Research Series*, pages 273–292. AGU, Washington D.C.

Orsi, A. H., Smethie Jr., W. M., and Bullister, J. L. (2002). On the total input of antarctic waters to the deep ocean: A preliminary estimate from chlorofluorocarbon measurements. *J. Geophys. Res.*, 107(C8):10.1029/2001JC000976.

Renfrew, I. A., King, J. C., and Markus, T. (2002). Coastal polynyas in the southern weddel sea: Variability of the surface energy budget. *J. Geophys. Res.*, 107(C6):10.1029/2000JC000720.

Stern, H. L., Rothrock, D. A., and Kwok, R. (1995). Open water production in arctic sea ice: Satellite measurements and model parametrizations. *J. Geophys. Res.*, 100(C10):20601–20612.

Stössel, A., Yang, K., and Kim, S.-J. (2002). On the role of sea ice and convection in a global ocean model. *J. Phys. Oceanogr.*, 32:1194–1208.

Thorndike, A. S., Rothrock, D. A., Maykut, G. A., and Colony, R. (1975). The thickness distribution of sea ice. *J. Geophys. Res.*

Zhang, J. and Hibler III, W. D. (1997). On an efficient numeric method for modelling sea ice dynamics. *J. Geophys. Res.*, 102(C4):8691–8702.