Tôhoku Geophys. Journ. (Sci. Rep. Tôhoku Univ., Ser. 5), Vol. 36, No. 4, pp. 550-554, 2003

Multiple Equilibrium Sea Ice States Induced by Ice Mechanics (Extended Abstract)

WILLIAM D. HIBLER III[1] and JENNIFER K. HUTCHINGS

International Arctic Research Center, University of Alaska : Fairbanks, 903 Koyukuk Dr., Fairbanks, Alaska 99775-7320, USA

(Received December 20, 2002)

Abstract: In order to investigate the possible effects of ice mechanics on inducing multiple equilibrium states of the arctic ice cover, a non-dimensional analysis of stoppage of flow through narrow passages due to ice arching arising from uniaxial plastic compressive strength is carried out. By adding growth rates to this analysis it is shown that multiple equilibrium states of a given ice cover under appropriate fixed thermodynamic and wind forcing are possible depending on when the ice flow is restrained. The ramifications of this phenomenon to numerical investigations of climate employing dynamic thermodynamic sea ice models is discussed.

Introduction

Circulation of the Arctic ice cover is significantly affected by ice mechanics, especially in the vicinity of narrow passages. The most notable example is the Fram Strait, where the outflow is substantial. On an annual basis the mass budget of the Arctic largely consists of a net growth of about 1 m of ice balanced by an equivalent amount exiting the Arctic Basin. Numerical investigations of the Arctic ice cover indicate that nonlinear ice mechanics can substantially affect the flow of ice both locally through the Fram strait (e.g. Ip *et al.*, 1991) and concomitantly throughout the Arctic Basin.

In the case of narrow passages, such as the Bering Strait, satellite observations (e.g. Sodhi, 1977) indicate ice motion can be totally stopped by the formation of static arches. Probably the most notable example of this is in the Nares Strait north of Baffin Bay where the flow of ice ceases every year around November. Stoppage of flow through this and numerous other narrow passages in the Canadian Archipelago plays an important role in the formation of the "Northwater Polyna" in Baffin Bay. Analytical (Sodhi, 1977) and numerical analysis of flow through narrow passages indicate that plastic rheologies with uniaxial compressive strengths can lead to total stoppage of flow. These analyses show that for a given wind or body forcing the ice strength divided by the channel width must reach a critical value for total stoppage. It is particularly notable that when scaled to the Fram Strait, results from non-dimensional numerical studies (Ip, 1993) of ice arching in narrow passages suggest the Fram strait is not far from the "arching" limit. This result that has long been qualitatively apparent in direct simulations (Hibler, 1980).

Since equilibrium ice thickness of the Arctic basin depends upon residence time, ice growth, and ice outflow in a nonlinear manner, the Arctic basin may have the capability for multiple equilibrium states. In this paper we present a non-dimensional analysis of ice flow through channels. It is shown that the formation of an ice arch allows the sea ice to be in a thin or thick state. Which state is approached depends upon the growth rate of the ice, suggesting that changes in Arctic temperature may trigger the ice cover to flip between different equilibrium states.

Characteristic of Plastic flow Through Narrow Passages

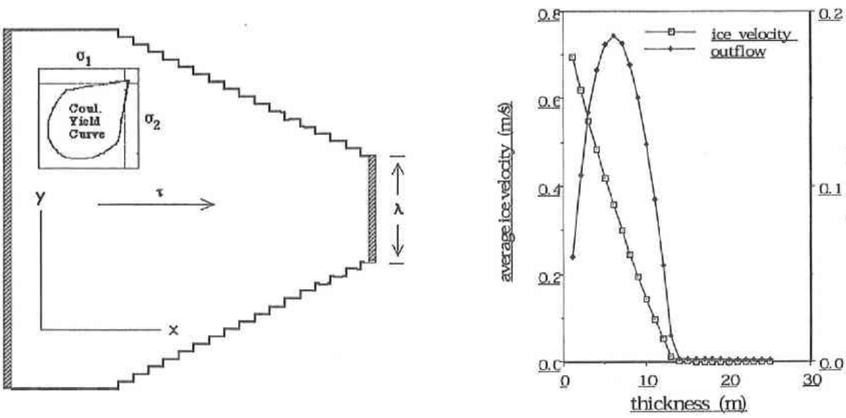
While arching is a statically indeterminate problem in that, for example, different shapes of arches will have different strengths and breaking limits, with the appropriate formulation it can be numerically analysed in a general non-dimensional manner (Ip, 1993). The basic idea is to consider a tapered channel as in Fig. 1, with parameters consisting of the length λ of the opening, the ice strength P and the wind stress $\rho_a c_a u_g^2$. For this system the x momentum equation in the absence of coriolis force is given by

$$0=\rho_a c_a u^2{}_g-\rho_a c_w u^2+\left(\frac{\partial\sigma_{xx}}{\partial x}+\frac{\partial\sigma_{xy}}{\partial y}\right). \tag{1}$$

Expressing x and y in terms of λ and stress in terms of P, we have after dividing by the wind stress the dimensionless equation

$$1=\beta-\gamma\left(\frac{\partial\sigma_{x'x'}}{\partial x'}+\frac{\partial\sigma_{x'y'}}{\partial y'}\right) \tag{2}$$

where primed values of stresses and x and y are dimensionless and β and γ are dimensionless parameters given by



(a) (b)

Fig. 1. (a) Numerical grid and (b) constant thickness ice outflow and velocity characteristics from plastic equilibrdum solution.

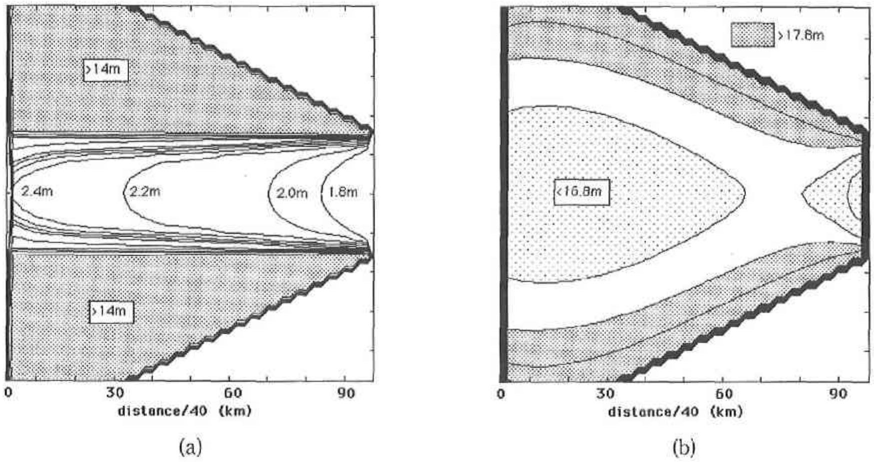


Fig. 2. Characteristic thickness patterns for (a) high and (b) low growth equilibrium simulations for the arching problem. Simulations initialised with $h=4$ m uniformally.

$$\beta=\frac{\rho_w c_w u^2}{\rho_a c_a u_g^2},\ \gamma=\frac{P}{l\rho_a c_a u_g^2}. \tag{3}$$

Consequently in dimensionless form the solution for β which is a measure of the ice velocity, should only depend on γ unless the geometry of the boundaries change.

To examine the character of the flow we consider the channel shown in Fig. 1a, discretised with 40 km resolution into a fifty by fifty grid. The shaded bands show regions where zero ice strength is assumed so the ice can freely flow into or out of the channel. A constant stress of $\tau=.4\ \mathrm{Nm}^{-2}$ in the direction of the arrow is used for the body force (i.e. the term $\rho_a c_a u_g^2$ in eqn.(1)). To simplify scaling a linear water drag (i.e. $\rho_w c_w u$) is used with $\rho_w c_w u=0.56$. For plastic rheology the modified Coulombic yield curve (Fig. 1a inset) of Hibler and Schulson (2000) is utilised. This rheology allows uniaxial compressive stress needed for static arching, i.e. some tensile stress. Ice strength is taken to scale linearly with thickness according to $P=4\times10^4\ h$. Solution of the equations of motion is carried out using the finite differences and relaxation procedure of Hibler (1979).

Figure 1b shows a dimensional plot of mean ice velocity and ice export as a function of ice thickness, or equivalently ice strength. Since linear water drag is used the same mean velocity curve will apply in non-dimensional form with the abscissa being $\gamma=\frac{P}{\lambda_\tau}$ and the ordinate being $\beta=\frac{\rho_w c_w u}{\tau}$. The basic character of the solutions is a gradual decrease of the ice velocity as the strength increases or the opening span (λ) decreases. At some point the velocity stops and an effectively static solution with an arch is obtained, and the system is close to motionless with higher velocities existing in an arch shaped region near the outflow opening.

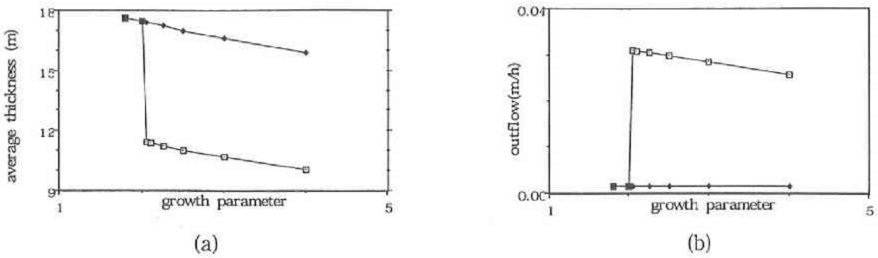


Fig. 3. Different equilibrium thicknesses for identical forcing for identical forcing for idealised geometry of Fig. 1. (a) Equilibrium thickness and (b) outflow versus growth parameter.

The ice outflow is particularly relevant to the multiple equilibrium problem. Since ice strength scales with thickness the outflow peaks for intermediate values of the flow where both the velocity and thickness are significant. For the small thickness, the outflow scales with h and hence becomes smaller as the velocity changes little with small strengths. For larger thicknesses, the outflow velocity is effectively negligible so even though the thickness is large there is very little mass being transported out. This occurs even though there is some mass in the velocity "cirque" formed near the downstream opening in the channel. It can be shown that the appropriate non-dimensional y axis value, call it α, scales as $\alpha \approx (P/\tau^2)\Delta$, where Δ is the outflow in dimensional form.

If ice growth occurs in the channel the outflow can be largely stopped or freely flowing depending on the rate of growth. This is illustrated in Fig. 2 where thickness characteristics are shown for growth rates inversely dependent upon thickness according to

$$f = \alpha[1/(h+0.4) - 0.005] \tag{4}$$

with α a variable and f in units of meters/hour. With high growth rates ($\alpha = 5/2.25$) the ice gradually forms a strong enough arching formation (Fig. 2a) to stop the outflow. In the case of weaker growth ($\alpha = 2.5$) the ice creates a narrow channel (Fig. 2b) in the ice pack through which ice flow occurs at a rapid enough rate to maintain a thin ice channel. Such features are very characteristic of the ice thickness patterns in the ice pack in regions near the Bering Strait (L. Shapiro, personal communication). This transition to total stoppage occurs rapidly with growth rate. Since both states are forced with the same wind, the physical notion is that there is potential for multiple equilibrium states with the same wind forcing dependent on the initial conditions. In particular, once the ice has stopped the growth rates could be reduced and still allow the ice to further thicken. Examples of such multiple equilibrium steady states are shown in Fig. 3. The thicker states were obtained by carrying out integrations with larger growth rates for 72 hours and then lowering the growth rate. Since once the growth is stopped, there is very small outflow, it is possible to obtain both thick and thin solutions for a very wide range of growth rates.

Concluding Remarks

The focus of this paper was to present some non-dimensional characteristics of the arching mechanism as it applies in conventional viscous—plastic and elastic—viscous—plastic sea ice dynamics models. These non-dimensional scaling characteristics may serve as a guide to determine when multiple equilibrium states may be expected, as in Fig. 3. This general analysis is a useful procedure which could be used in current numerical investigations of climate. We have shown that nonlinear ice mechanics may play a role in controlling the sea ice outflow through straits from the Arctic Basin. It is possible that multiple equilibrium states for the Arctic ice cover are possible for identical forcing. Essentially identical forcing may produce a thick or thin ice state depending on the thickness of the initial ice cover and the ice growth rate. The non-dimensional analysis of arching in narrow straits suggests that stoppage of flow through the Fram Strait is possible, which may have major implications for the climate. An investigation of stoppage at the Fram Strait is presented by Hibler & Hutchings [2002], where it is found a dynamic—thermodynamic sea ice model may maintain two stable and one unstable equilibrium states. While such multiple equilibrium states may be outside the range of present climate conditions, their existence may affect the response of the model to major changes in the wind fields related to interdecadel and climate variability. This highlights the importance of including non-linear ice dynamic models in climate simulation. The simple interpretation that Arctic ice circulation is highly correlated to the wind is unlikely to apply in all climate scenarios, and rheological models that do not support arching are unlikely to capture true ice behaviour. Future work will include extending the Hibler & Hutchings [2002] experiment to a full climate model to investigate how switching between multiple equilibrium states of the Arctic ice might affect global climate and when this switching might occur.

References

Hibler, W. D., III, 1979 : A dynamic thermodynamic sea ice model, *Journal of Physical Oceanography*, 9(4), 815-846.

Hibler, W. D., III, 1980 : Modeling a variable thickness sea ice cover, *Monthly Weather Review*, **108**, 1943-1973.

Hibler, W.D., III and E.M. Schulson, 2000 : On modeling the anisotropic failure and flow of flawed sea ice, *J. Geophys. Res.*, **105**(C7), 17105-17119.

Hibler, W.D., III and Hutchings, J.K, 2002 : Multiple equilibrium Arctic ice cover states induced by ice mechanics, Proceedings of the IAHR conference, Dunedin New Zealand.

Ip, C. F., 1993 : Numerical Investigations of Different Rheologies on Sea-Ice Dynamics, Thayer School of Engineering, Dartmouth College Ip, C.F., W.D. Hibler III, and G.M. Flato, 1991 : On the effect of rheology on seasonal sea ice simulations, *Annals of Glaciology*, **15**, 17-25.

Sodhi, D.S., 1977 : Ice arching and the drift of pack ice through restricted channels, CRREL Rep., 77-18, Cold Regions Res. and Eng. Lab., Hanover, N.H.