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On Slowly Drifting Sea Ice with a Corrugated Underside

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ABSTRACT

The oceanic mass transport induced by wind-driven sea ice with a corrugated bottom is investigated theoretically by using a Lagrangian description of motion. The bottom corrugations are sinusoidal with infinitely long crests and small amplitudes. The ice drift is rectilinear and slow enough for a suitably defined fluid Reynolds number R to be small. The solutions are written as a 2-parameter expansion in R and the nondimensional corrugation amplitude ε. The solutions to $O(R^1\varepsilon^2)$ yield the interaction between the basic Ekman current and the nonlinear displacement field due to the corrugations. The steady mean solution to this order is obtained, and the results are discussed for various angles between the ice-drift velocity vector and the bottom striations as well as for various ratios between the corrugation wavelength and the Ekman depth. The deflection angle α between the ice-drift direction and the wind stress that drives the ice is compared to the corresponding angle α_0 for flat-bottomed ice. For thin ice with negligible internal friction, it is found that $\alpha > \alpha_0$ for nondimensional corrugation wave numbers larger than 2.23. In this case α has a maximum when the drift vector is 22.5° to the left of the striations (in the Northern Hemisphere). For smaller wave numbers one may have $\alpha < \alpha_0$, with a minimum value for α when the motion of the ice is 22.5° to the left of the cross-striation direction. For thicker ice and nonnegligible internal friction, maximum and minimum deflection angles are still related to drift directions that are 90° out of phase, but maximum deflection angles now occur for drift directions somewhat larger than 22.5° to the left of the striations.

INTRODUCTION

The observation that sea ice does not drift along the wind direction, but, in the Northern Hemisphere, somewhat to the right of this direction, is originally due to Nansen (1902). He found that the *Fram*, frozen in the ice, consistently drifted 20°-40° to the right of the surface wind on its journey across the Polar Sea. Nansen attributed this fact to the joint action of wind stress, the ice-bottom friction force and the Coriolis force. From the drift of the *Maud* on the North-Siberian shelf, Sverdrup (1928) estimated the average deflection angle between the surface wind and the ice drift to be about 33°. For a recent discussion of ice-ocean response to wind forcing, we refer to Omstedt, Nyberg and Leppäranta (1996).

In the polar oceans the drifting ice exhibits a bottom topography with many different scales, from small ripples to large keels, e.g. Gow and Tucker (1990). The presence of bottom corrugations will affect the drift direction of the ice relative to that of the wind. Discussing the possible ship-towing of large ice floes with sinusoidal bottom corrugations, Wang (1988) calculated the averaged Eulerian flow field in the water induced by ice moving at constant speed and the corresponding resistance to this motion. In this paper we let the wind be the driving agency. Furthermore, we apply a Lagrangian description of motion. This enables us to calculate the actual mean particle drift in the ocean induced by the wave-shaped corrugations of the moving ice. In this way we can determine the motion of tracers and algae close to the ice-water boundary. A similar approach has successfully been used for the study of free ocean-surface waves, e.g. Chang (1969), Ünlüata and Mei (1970), and Weber (1983a,b). From the Lagrangian analysis we calculate the mean stress at the corrugated ice-water boundary. The gradient of the internal stress in the ice is modelled in a very simple way, e.g. Sverdrup (1928). Assuming a balance of forces per unit area of the ice, the ice-drift direction in relation to the wind direction is discussed for various orientations of the bottom striations.

MATHEMATICAL FORMULATION

Consider a large ice sheet of mean thickness D_i overlaying an incompressible, viscous ocean of constant density ρ. The motion will be described in a Cartesian coordinate system, where the horizontal x_*– and y_*–axes are directed along the smooth, or undisturbed, ice-water interface. The z_*–axis is vertical, and positive upward. The ocean and the reference system rotate about the z_*–axis with a constant angular velocity Ω. In this system the ice moves at constant speed U in a direction that makes an angle β with the x_*–axis. The underside of the floating ice has sinusoidal corrugations with wavelength λ. The length of the crests is assumed to be much larger than λ. Furthermore, the crests are always directed in the y_*–direction (Fig. 1). In the present asymptotic limit they are taken to be infinitely long and the ice sheet to be unlimited in the horizontal directions. The Fig. 1 sketch also depicts the deflection angle α between the ice-drift direction and the wind stress at the ground. We will return to this angle later on

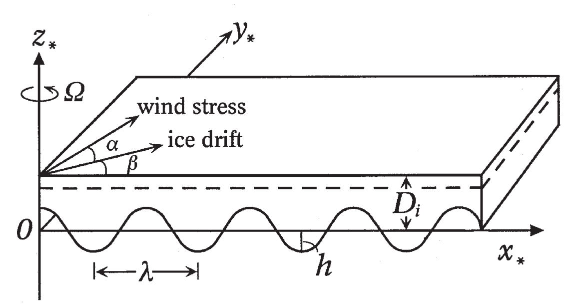

Fig. 1 Figure sketch

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KEY WORDS: Sea-ice drift, under-ice topography, Lagrangian mass transport.