P1.1 THE EFFECTS OF KEELS AND FROZEN LEADS ON UNDER ICE TURBULENCE

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1. INTRODUCTION

In recent years, climate researchers have identified sea ice as a key component in the coupled ocean/atmosphere climate system. Sea ice has a much higher albedo relative to open ocean, so that small changes in sea ice coverage can have a large effect on upper ocean heating during the summer. If upper ocean warming leads to greater ice edge melting, then a feedback mechanism can exist leading to greater reduction in ice coverage and more warming. Accurate prediction of sea ice coverage is therefore critical for understanding the heat budget of the polar regions.

Of particular importance is the relative strength of melting under the ice versus the ice edge in leads. Strong solar heating during the summer in combination with light winds can cause a build up of fresh water in leads and just beneath the sea ice. During these conditions, stratification beneath the ice reduces the flux of heat from the ocean mixed layer to the ice bottom, which may limit the melting process. Lateral melting in leads, however, can continue via surface water that is directly heated by solar radiation.

When winds increase to sufficient levels, this scenario is disrupted as ice imparts momentum to the upper ocean. Observations from the SHEBA field experiment indicate that strong winds can cause rapid mixing of the surface fresh layer, leading to increased bottom melting as mixed layer water is transported vertically.

In this study we utilize a large-eddy simulation (LES) model to examine how ice motion causes increased turbulence in the upper ocean.

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Experiments are performed using the coupled ice-ocean LES presented in Skyllingstad and Denbo (2001) with modifications to include under ice variability from leads and keels. We are interested in three main scenarios as represented in Figure 1. In

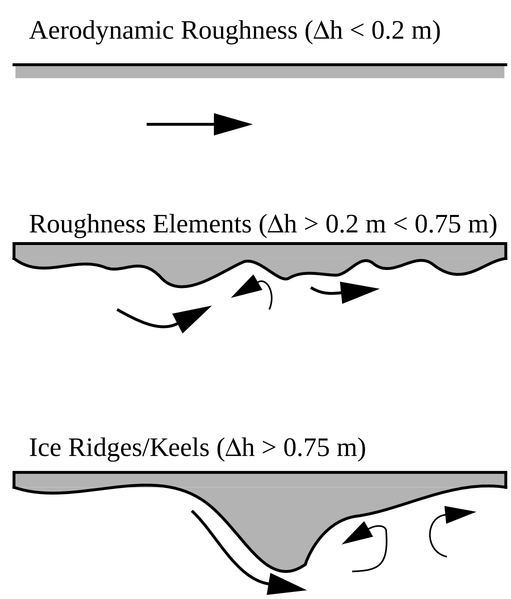

Figure 1. Schematic showing effects of ice bottom topography on upper ocean flow.

the first scenario, simulations are performed for ice with relatively small variations in depth that can be represented as an aerodynamic roughness. In this case, the main effect of the ice is to act as a uniform drag on the upper ocean, causing the formation of shear and shear-induced turbulence.

In the second and third cases, ice thickness variations are explicitly resolved by the LES model by changing the location of the uppermost grid point in the model. Our approach in modeling ice

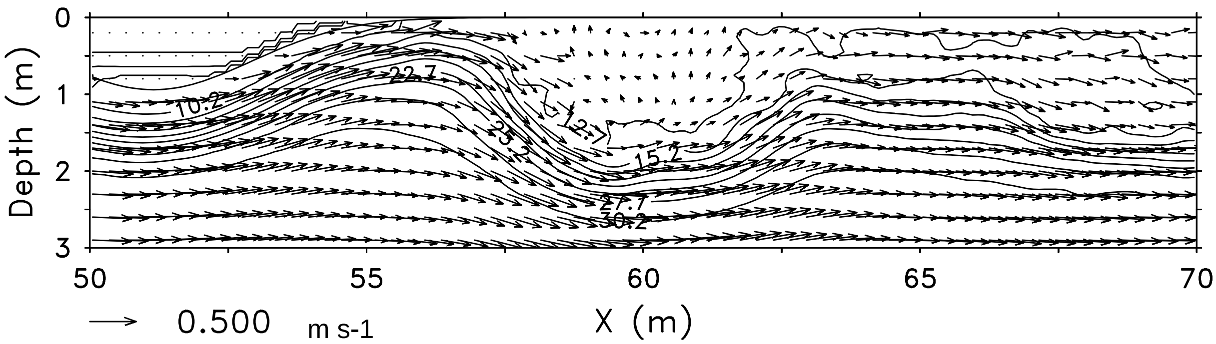

Figure 2. Downstream distance - depth cross section showing salinity (psu) and ice relative velocity (m s^{-1}after 6 minutes. The keel is located at x = 51.2 m and has a depth of ~0.8 m.

bottom variations is through step orography, or by simply setting the velocity and pressure in ice filled grid cells to zero. This method, when combined with an enstrophy conserving scheme (Tripoli 1992) for momentum, yields a smooth result without significant numerical effects (e.g. see Gallus and Klemp 2000). Normally, variations in surface orography are handled using terrain-following coordinates. However, coordinate transformations cannot easily represent steep orography as produced by ice keels or lead edges, and may affect the behavior of turbulence through implicit changes in the grid resolution.

Simulations were initialized at rest with a constant imposed ice velocity of -0.4 m s^{-1}. We could not realistically increase the ice velocity as would occur in actual wind events because of the long time scale of storms and the very small time step required by the LES model. As a consequence, our results do not represent the effects of orography on fully-developed turbulent flows, but are more representative of the turbulent processes directly attributable to ice bottom features.

Here, we focus only on the keel scenario (Scenario 3 in Fig. 1) and examine two, substantially different initial vertical salinity profiles. We also investigate the sensitivity of the boundary layer to changes in the keel depth. In one case the keel is made very shallow relative to the mixed layer, while in the other it is deep. In these preliminary experiments, periodic boundary conditions are used in the lateral direction, which has the effect of simulating a series of ice keels. To minimize the effects of the keel generated turbulence that is recirculated through the periodic boundary, we use a channel model configuration with 1024 grid points in the ice motion direction, and 128 points in the cross flow direction. In the first case, profiles with a shallow (1-m) surface fresh layer are used, representing conditions found in July during the SHEBA field program. The model domain for this case contained 50 levels and a grid spacing of 0.1 m. In the second case, a relatively uniform profile was used representing conditions during late summer when wind driven ice motion has caused the surface fresh layer to mix downward to the seasonal pycnocline. A similar model configuration was used in this case, but with 60 vertical levels and grid spacing of 0.5 m. Keels are prescribed using an exponential function in the *x* direction, with a sinusoidal variation along the crest of the keel. The sinusoidal variation is set to 2 peaks for the cases presented here, with a 20% variation in the height. Two keel depths are examined in each experiment. For the fresh layer case, depths are set to 0.2 and 1.2 m, and in the mixed layer case, depths are set to 1.0 m and 4.0 m.

2. RESULTS

Our initial experiment centers on understanding how under-ice keels affect mixing in very stratified conditions common in the summer season. In these cases, fresh water just beneath the ice isolates the ice motion from the rest of the upper ocean. Keels disrupt the flow by blocking the fresh layer and generating strong internal wave motions in the downstream direction. Cross section plots of the salinity and velocity fields after only 6 minutes (Fig. 2) demonstrate this effect. Ice motion is toward the negative *x* direction, hence the relative velocity flows toward positive *x*. The keel is located at $x = 51.2$ m and is followed by a region of strong upward motion and stagnation as the stable layer is perturbed by the keel. Downstream from the stagnation zone, the flow develops a more defined boundary layer with salinity increased from ~6 psu upstream of the keel (not shown) to ~12 psu because of enhanced vertical mixing.

The effects of the 1.0 m keel are emphasized by comparing the average salinity profile with a longer simulation (18 minutes) having a keel depth of 0.2 m (Fig. 3). As Fig. 3 shows, the deep keel produces a region of well-mixed fluid just beneath the ice. In contrast the shallow keel case still has significant stratification at the ice base, even after 18 minutes.

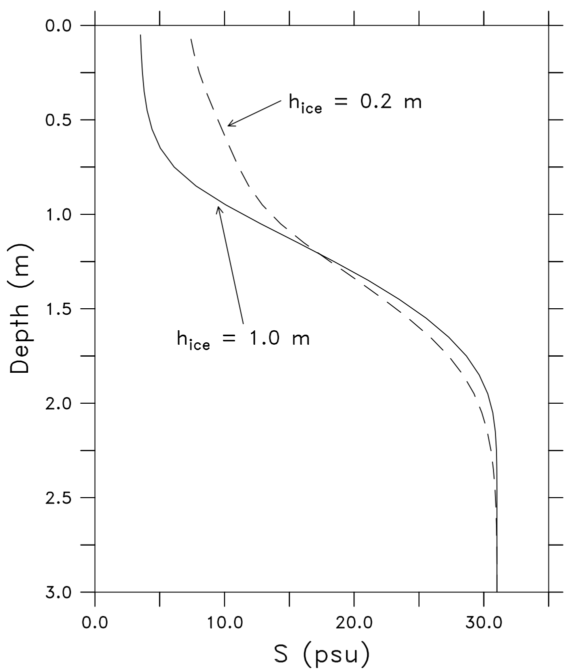

Figure 3. Plots of the horizontally averaged salinity (psu) after 6 minutes (h_{ice} = 1.0 m) and 18 minutes (h_{ice} = 0.2 m).

In our second experiment, we examine a typical late summer/winter situation where the upper ocean is relatively well-mixed. Our goal in this case is to determine if keels cause appreciably greater mixed-layer turbulent exchange relative to cases without significant under-ice orography. Increased turbulence during the melt season is important because it allows for more efficient transfer of heat from the mixed layer to the ice bottom, promoting greater melting.

Mixing in this case is generated mostly by turbulent eddies without wave instability as noted

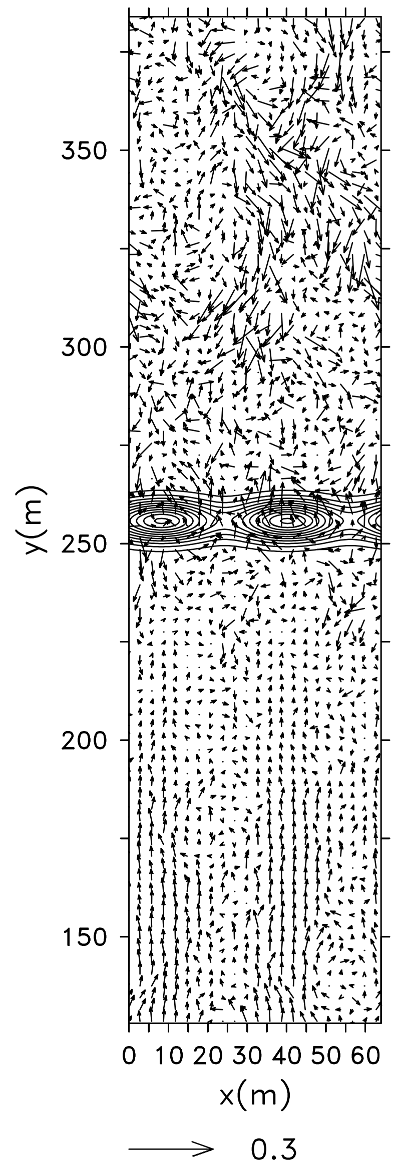

Figure 4. Horizontal cross section showing velocity vectors (m s^{-1}) after 30 minutes. Also shown are the ice bottom orography (m).

in the stable simulation presented above. These eddies are shown by a horizontal cross section plot of the velocity fields above the keel (Fig. 4) for the deep keel case. The presence of the keel greatly affects the strength of turbulence; eddies downstream from the keel ($x > 256$ m) are much stronger than the upstream eddies. Some of this difference could be due to the shortness of the simulation (30 minutes), which is an issue that will be addressed in our continuing research

The effects of the keel are more clearly shown by examining the source terms of turbulence in the turbulence kinetic energy equation for the shallow and deep keel cases, as presented in Fig. 5. This plot shows the combined TKE forcing from advection and shear production terms, which quantify turbulence generated by the physical forcing of the keel and shear generated from the ice motion. As Fig. 5 demonstrates, increasing the keel depth by a factor of 4 has a significant impact on the generation of TKE, particularly at the keel depth. For the deep keel case, two maxima are

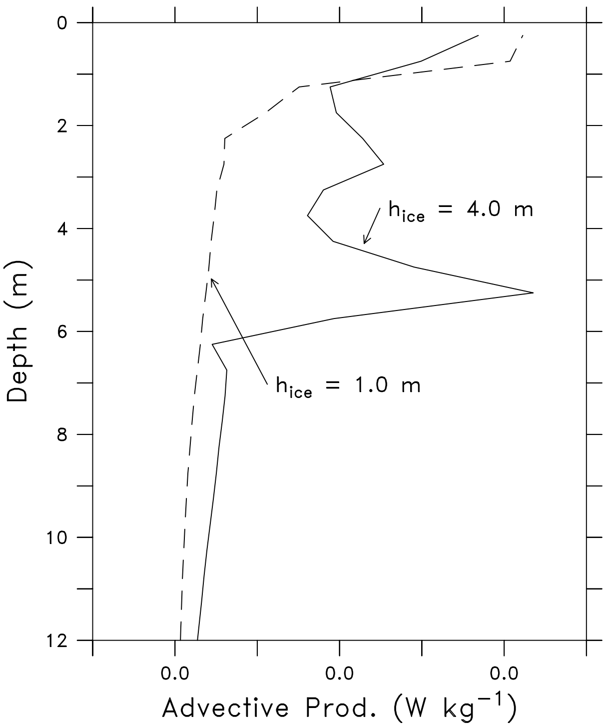

Figure 5. Horizontally averaged advective and shear production from the turbulence kinetic energy equation.

indicted in the profile, one associated with shear production near the ice bottom, and a second at ~5 m from advective production at the keel. In the shallow keel case, advective and shear production near the bottom of the ice decreases rapidly to a region below ~3 m where shear production becomes the dominant source of turbulence.

3. CONCLUSIONS

The results of our preliminary experiments indicate that, as expected, keels can cause a significant enhancement of turbulence beneath sea ice. The challenge is to develop enough understanding of the turbulence processes so that improvements can be made to boundary layer parameterizations. One encouraging result from these experiments suggests that, in the absence of strong stratification, keels may be included in boundary layer parameterizations by simply increasing the local roughness length. As shown by a logarithmic plot of the average velocity profiles from the two keel depth cases (Fig. 6), both cases can be described using a log-linear profile. This implies that the roughness length can be scaled to account for keel induced mixing, given enough information about the average keel depth and distribution for a section of sea ice.

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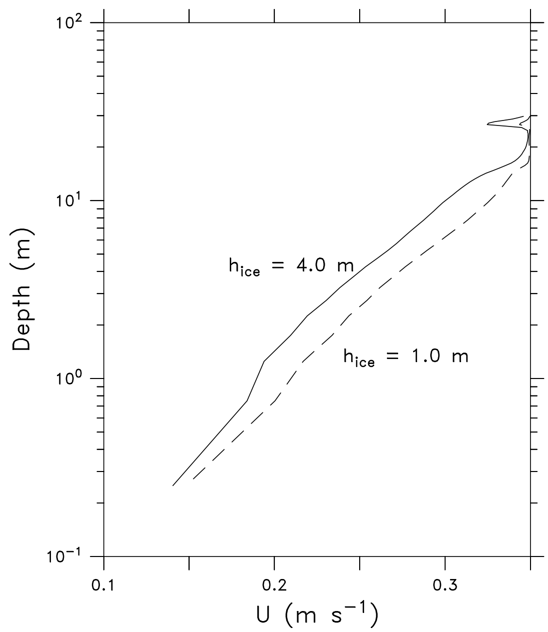

Figure 6. Horizontally averaged ice-relative velocity from case 2 with two different keel depths.

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