Comment on A Coupled Dynamic-Thermodynamic Model of an Ice-Ocean System in the Marginal Ice Zone

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Comment on “A Coupled Dynamic-Thermodynamic Model of an Ice-Ocean System in the Marginal Ice Zone” by Sirpa Häkkinen

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The recent article by Häkkinen [1987] creatively addresses a number of important dynamic and thermodynamic processes in the marginal ice zone (MIZ). We believe that her study will stimulate further research on the coupled ice-ocean system. For now, we would like to offer the following discussion of the need to augment the entrainment equation to include surface buoyancy flux for general application to the MIZ.

**INCLUSION OF BUOYANCY FLUX IN ENTRAPMENT FORMULATION**

In Häkkinen’s study of the coupled ice-ocean system the ocean is considered to have two layers. An essential part of the thermodynamics is the mixed layer entrainment of the lower layer by the surface layer. However, entrainment was parameterized using only the friction velocity at the ocean surface, including an ad hoc e-folding depth dependence from Pollard et al. [1983]:

\[ w_e = 6u*^2 \exp\left(-h_i/h_0\right)/(C^* \alpha + \gamma h_1) \]  

(1)

where \( h_i \) is the upper layer depth, \( u_e \) is the surface water friction velocity, \( \gamma^* \) is the reduced gravity, \( h_0 \) is the length scale for e-folding damping, and \( C^* \) is a parameterization for unsteadiness in the turbulent kinetic energy (TKE) budget. The values of \( h_0 \) and \( C^* \) are specified by Häkkinen to be 20 m and 0.03 m/s, respectively. Equation (1) is insufficient for general application to the MIZ because it does not include buoyant production or damping caused by the buoyancy flux at the ocean surface, \( B_0 \). This neglect of the buoyancy flux is inconsistent with the combined contributions to the mixed layer buoyancy that will be associated with the assumed surface heat loss of 500 W/m², the assumed evaporation rate of 0.005 m/d, and a predicted freezing rate of about 0.1 m/d. As an example we will provide a one-dimensional evaluation of the heat budget that will demonstrate the need to improve (1).

Including \( B_0 \), the recommended form for the entrainment parameterization is

\[ w_e = (c_1 u_e^3 - c_2 B_0 h_1)/\gamma h_1 \]  

(2)

The value of \( c_1 \) is about 2, but it may be reduced for deeper mixed layers (for comprehensive reviews, see Zilitinkevich et al. [1979], Garwood [1979], Gaspar [1987], and Gallagher [1987]. In tested [Martin, 1985; Gaspar, 1987] parameterizations for the net heat production of TKE less dissipation, the effective value of \( c_1 \) is exponentially reduced on a vertical scale of \( u_e / f \):

\[ c_1 \sim 2 \exp(-fh_1/u_e) \]  

(3)

For Häkkinen’s numerical simulation, \( c_1 \) would be reduced to about 1. The value of \( c_1 \) in (2) is a function of stability. Stull [1976] summarizes values of \( c_2 \) indicating \( c_2 \sim 0.2 \) for free convection (\( B_0 < 0 \) and \( u_e \sim 0 \)). With the strong wind forcing in the Häkkinen simulation, \( c_2 \) may be somewhat larger.

For the case of an ocean surface just beginning to freeze (we will assume that the fractional ice cover is initially small) the surface buoyancy flux has three components:

\[ B_0 = -\alpha_0 Q_w/\rho_w c_p - \beta_0 (F - M)(S_1 - S_f) - \beta_0 (E - P)S_1 \]  

(4)

Here \( Q_w \) is the net heat loss from the water surface, \( F - M \) is the freezing rate minus the melting rate, \( S_1 - S_f \) is the water surface salinity minus the ice salinity, and \( E - P \) is the evaporation rate minus the precipitation rate. To contrast the differences between (1) and (2), we shall compute \( B_0 \) and \( w_e \) for Häkkinen’s simulation of the formation of new ice which occurs in a region that is nearly horizontally homogeneous during the first day [see Häkkinen, 1987, Figure 4c]. In this region we evaluate (2)-(4) using her values: \( E - P = 0.005 \) m/d, \( F - M = 0.1 \) m/d, \( S_f = 9.60 \) g/kg, \( S_1 = 34.60 \) g/kg, \( S_2 = 34.95 \) g/kg, \( Q_w = 500 \) W/m², \( h_1 = 75 \) m, \( T_f = -1.89 \) K, \( T_i = 0 \) K, \( \alpha = 0.025 \times 10^{-3} \) K⁻¹, \( \beta = 0.79 \), \( f = 1.44 \times 10^{-4} \) s⁻¹, \( g = 9.81 \) m/s², \( c_p = 4.186 \times 10³ \) J kg⁻¹ K⁻¹, and \( \rho_w = 1028 \) kg/m³. We find that

\[ -c_1 B_0 h_1 = 0.2(2.1 + 16.6 + 1.2) \times 10^{-6} \text{ m}³/\text{s}³ \]

(5)

for the sum of the surface heat flux, freezing, and evaporation contributions, respectively. Assuming an open water wind stress of 3 dyn/cm² (or \( u_e = 0.017 \) m/s) and assuming that \( c_1 = 1 \),

\[ c_1 u_e^3 = 5.2 \times 10^{-6} \text{ m}³/\text{s}³ \]  

(6)

The buoyancy jump at the base of the mixed layer (reduced gravity)

\[ \alpha^* = \beta_0 (S_2 - S_1) - \alpha_0 (T_2 - T_i) = 2.29 \times 10^{-3} \text{ m}³/\text{s}³ \]  

(7)

Summing the buoyancy flux and the wind-stirring contributions to the entrainment mixing, (2) is used to compute the entrainment heat flux into the surface layer:

\[ Q_e = \rho_w c_p A T w_e = 246 \text{ W/m}² + 188 \text{ W/m}² = 434 \text{ W/m}² \]  

(8)

Conversely, using (1) with an excessively reduced wind mixing and totally neglecting the surface buoyancy flux, we calculate a value for \( Q_e \) of only 35 W/m². Clearly, the entrainment rate, the heat and salt budgets, and the rate of freezing will be significantly affected by the large entrainment heat flux. The freezing rate predicted by Häkkinen of about 0.1 m/d was dependent upon a net mixed layer heat loss of 465 W/m²; 500 W/m² lost to the atmosphere less 35 W/m² gained by entrainment. From the large entrainment heat flux predicted in (8) the net heat lost from the mixed layer should be reduced by about 86%. A slightly greater entrainment heat flux would prevent freezing entirely. However, an important feedback
Feedback Mechanisms

The alternative entrainment parameterization suggested here, equation (2), also implies a positive/negative thermodynamical feedback mechanism in the MIZ, as shown in Figure 1. The positive feedback mechanism is that the increased (decreased) heat loss $Q_\text{H}$ due to ice melting (freezing) intensifies (weakens) the entrainment, which further strengthens (decreases) the ice melting (freezing) rate. However, a negative feedback mechanism is that the increased upward (downward) buoyancy flux caused by the salinity flux due to ice melting (freezing) weakens (intensifies) the entrainment, which further decreases (strengthens) the ice melting (freezing) rate.

The thermal expansion coefficient of seawater, $\alpha$, is very sensitive to temperature and is small at the freezing point. Therefore, the negative feedback mechanism mentioned here may be more important, in general, than the positive feedback mechanism.

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References


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