Modeling the thermodynamics of a sea ice thickness distribution

2. Sea ice/ocean interactions

M. M. Holland, J. A. Curry, and J. L. Schramm
Department of Aerospace Engineering, University of Colorado, Boulder

Abstract. In this paper we examine the coupling of an ice thickness distribution model with an ocean mixed layer model. The annual cycle of the modeled mixed layer temperature, salinity, and depth are compared to observations from the drifting ice stations of the Arctic Ice Dynamics Joint Experiment (AIDJEX). The role of the ice thickness distribution in determining the ice/ocean coupling is examined. We find that the ice thickness distribution is important for the exchange of heat, salt, and fresh water between the ice and the ocean, especially with regard to the effects of thin, first-year ice. Several different parameterizations of the ice/ocean turbulent heat exchange are compared. The results indicate that the storage of heat in the mixed layer is important for determining the annual average ice thickness. Double diffusion and the stabilizing effects of meltwater also impact the exchange of heat between the ocean and ice cover. Questions remain as to the relative importance of these processes and their accurate parameterization in ice/ocean coupled models.

1. Introduction

The presence of sea ice modifies ocean/atmosphere interactions by acting effectively as a filter between the atmosphere and ocean in the exchange of heat, momentum, and other quantities. The presence of ice results in dual boundary layers, at the ice/atmosphere and the ice/ocean interfaces. This paper focuses on the exchanges of heat and salt that occur at the ice/ocean interface and on how this exchange relates to the mass balance of the ice pack.

The sensitivity of the growth and overall thickness of sea ice to the flux of sensible heat at the ice/ocean interface was first illustrated by the model simulations of Maykut and Untersteiner [1971]. From sensitivity studies conducted using a one-dimensional thermodynamic model of sea ice, Maykut and Untersteiner determined that undeformed ice received an annual average of about 2 W m⁻² from the ocean. Because of the cold halocline between the ocean mixed layer and the deeper warm layer below, it is unlikely that heat from the Atlantic ocean directly affects the ice pack [e.g., Coachman and Barnes, 1963].

An alternative source of energy for the turbulent heat flux at the base of the ice was proposed by Maykut [1982]. He suggested that shortwave radiation entering the ocean mixed layer through leads and thin ice could account for an annual average of about 3.2 W m⁻² absorbed below the bottom of the pack ice. Ebert et al. [1995] used a one-dimensional sea ice model that included an ice thickness distribution to determine that 4% of the total incoming shortwave radiation was transmitted into the upper ocean. It was shown that ponded ice transmits more radiation to the ocean than does unponded ice but that most of the radiation was transmitted to the ocean mixed layer through thin ice and leads. In an analysis of data from the 1975 Arctic Ice Dynamics Joint Experiment (AIDJEX), Maykut and McPhee [1995] estimated that peak values of the solar heat input to the upper ocean through leads reached 40-60 W m⁻² during August.

Solar radiation absorbed by the upper ocean does not necessarily result in the instantaneous transfer of heat to the ice. Maykut and McPhee [1995] and Perovich and Maykut [1990] indicate that the ice-covered ocean mixed layer can store heat for extended periods. Direct measurements of turbulent heat flux at the ice/ocean boundary layer were reported by McPhee et al. [1987] from observations during the 1984 Marginal Ice Zone Experiment (MIZEX). They found that the ice/ocean heat flux was dominated by molecular effects in thin sublayers near the ice/water interface that had no direct counterpart in the momentum flux process.

The importance of salinity in determining upper ocean buoyancy and ice freezing and ablation is described by McPhee et al. [1987]. Melting and freezing of ice at the ice/ocean interface is complicated by dependence of the freezing point on salinity. When seawater freezes, brine pockets become trapped in the ice, while the remainder of the salt is flushed back into the ocean. As the ice ages, brine drainage occurs, resulting in old ice having lower salinities than young ice. The flux of fresh water into the ocean mixed layer includes the effects of ice ablation and accretion, snowmelt, brine drainage from the ice as it ages, fresh water inflow, and precipitation and evaporation in the leads. Melting of weakly saline ice or brine rejection occurring during accretion induces variations of the surface water salinity that affect the dynamics of the upper ocean. During ice accretion, brine rejection gives rise to convection and causes entrainment at the bottom of the mixed layer. In the polar oceans the pycnocline is warmer than the mixed layer, so convective entrainment may bring some heat from the deeper layers into the mixed layer, depending on the upper ocean temperature and salinity structure.

The ice thickness distribution complicates this exchange of heat and salt, particularly with regard to leads, pressure keels,
and ice of different salinities. Because of varying ice salinities for ice of different age and thickness, it is impossible for all ice categories to be in simultaneous equilibrium with the ocean mixed layer, which is in general horizontally homogeneous. For example, salty, young ice may be melting at the base, while older, less saline ice may be freezing at the base. The importance of the ice thickness distribution in determining the salinity fluxes has been examined by Maykut [1982].

The annual cycle of heat and salt exchange between the ice and ocean is critical for understanding and modeling ice dynamics and thermodynamics, evolution of the ocean mixed layer, and ocean biological processes. Processes such as rapid melting and freezing, meltwater runoff, changes in ice concentration, and modifications to ice bottom roughness result in strong ice/ocean interactions that can change the characteristics of the sea ice and the upper ocean. The essential portion of the coupling is the simulation of the interfacial fluxes between the ocean and ice that are strongly dependent on the ice thickness distribution.

Previous attempts to model the coupled Arctic ocean mixed layer/sea ice system have generally considered a mixed layer model coupled to a relatively simple sea ice model, in which open water and a single ice thickness exist. The simplest representation of the ocean mixed layer that has been employed in ice/ocean studies is of a slab of constant depth [e.g., Toole, 1981; Ebert and Curry, 1993]. In addition, several one-dimensional modeling studies have employed variable depth mixed layers under an ice pack. These include both integral models of the mixed layer [e.g., Pollard et al., 1983; Lemke and Manley, 1984; Lemke, 1987; Fichefet and Gaspar, 1988] and turbulence closure models [e.g., Ikeda, 1986; Mellor and Kantha, 1989; Redi and Warn-Varnas, 1990]. In general, these studies have concluded that a variable depth mixed layer is important for determining the heat budget of the ice/ocean system and the growth rate of the ice pack. Pino et al. [1991], using a three-dimensional ice/ocean coupled model, showed that the inclusion of a turbulent mixed layer model improves the simulation of the ice thickness distribution of the Arctic basin.

In contrast to the aforementioned studies, we examine the coupling of the ice and ocean using an ice thickness distribution (ITD) model coupled to a bulk ocean mixed layer model. The use of an ice thickness distribution model allows us to simulate the high spatial variability apparent in the observed sea ice. We assess the performance of this coupled system in reproducing the observed annual cycle of ocean mixed layer characteristics and ice/ocean fluxes. In section 2 a description of the model is given, focusing on the ocean mixed layer component and the ice/ocean interactions. Section 3 examines the annual cycles simulated by the model and compares them to in situ data. Results from several sensitivity and comparison studies are discussed in sections 4 and 5. The comparison studies allow us to assess the importance of the ice thickness distribution on ice/ocean interactions. The first of these studies is a comparison of ice/ocean interfacial heat fluxes computed using three different ice thickness distributions, including the full ITD obtained in the baseline simulation, a single ice category distribution, and an imposed seven category distribution. In addition, we compare an ice/ocean interfacial flux parameterization that explicitly accounts for the ice thickness distribution with one that does not. The model sensitivity to different parameterizations of basal heat flux is also examined.

2. Model Description

The model used here is a coupled ice-ocean model, with specified surface forcing. A schematic of the model is presented in Figure 1. The sea ice model is a one-dimensional thermodynamic representation of an ice sheet that is separated into a number of ice classes characterized by their thicknesses, areas, surface characteristics, salinities, and ages. The sea ice model is coupled to a bulk ocean mixed layer model.

2.1. Sea Ice

The sea ice model is described in detail in a companion paper [Schramm et al., this issue] (hereinafter referred to as part 1); only a brief summary is given here. The sea ice is modeled as a distribution of ice slabs with different properties. These properties include ice thickness, age, snow cover, melt pond cover, and salinity. Thus a sea ice thickness distribution is obtained that allows a statistical representation of the high spatial variability that occurs in the observed sea ice. The basic sea ice growth and decay cycle is controlled by the conduction of heat through the ice and a balance of fluxes at the upper and lower ice interfaces. The model has a complex surface albedo parameterization that takes into account the ice surface characteristics, thickness, and age and the area and depth of meltwater ponds during the summer. Treatment of the disposition of shortwave radiation in the ice is described by Ebert et al. [1995].

The ice model represents a drifting parcel of ice. It contains some parameterizations of dynamic processes in that the modeling of ice ridging and the opening and closing of leads is based on specified divergence and shearing. Leads are opened through the net divergence of the ice field, the ridging process, and lateral melting due to the absorption of solar radiation. When the water temperature in the lead drops below freezing, ice is grown vertically. This provides a source of thin ice during the winter months. A minimum lead fraction of 0.15% is maintained throughout the winter by the dynamic processes.

2.2. Upper Ocean

The one-dimensional integral ocean mixed layer model described by Gaspar [1988] is used. This model has been applied to the Arctic Ocean by Fichefet and Gaspar [1988]. It is assumed that the mean temperature and salinity are uniform within the upper oceanic mixed layer and thus the equations for these properties can be integrated across the mixed layer depth. Changes in the mixed layer temperature and salinity are caused by exchanges with the atmosphere or sea ice above and the deeper ocean below. In order to close the system, an equation governing the evolution of the mixed layer depth is needed. This is obtained from the turbulent kinetic energy (TKE) budget of the mixed layer, following Gaspar [1988]. A parameterization for turbulent dissipation is included which incorporates rotation and stability effects.

Following Gaspar [1988], the following equations are obtained:

\[ h_m \frac{dT_m}{dt} = \frac{1}{\rho g h_m} \left[ F_{\text{SOL}} \left( 1 - I(h_m) \right) + F_{\text{NSOL}} \right] - w_c \Delta T \]

\[ - K_h \frac{dT}{dh} \bigg|_{h_m} \]

\[ h_m \frac{dS_m}{dt} = \frac{1}{\rho_0} F_{\text{SALT}} - w_c \Delta S - K_s \frac{dS}{dh} \bigg|_{h_m} \]

(1)

(2)
in which \( h_m \) is the mixed layer depth, \( T_m \) and \( S_m \) are the mixed layer temperature and salinity, \( F_{\text{sea}} \) is the solar component of the heat flux entering the ocean, \( F_{\text{non}} \) is the nonsolar component of the ice-ocean interfacial heat flux, \( I(z) \) is the fraction of the solar radiation that penetrates to depth \( z \), \( F_{\text{salt}} \) is the flux of salinity due to ice ablation and accretion processes and fresh water inflow, \( w_e \) is the entrainment velocity, \( \Delta T \) and \( \Delta S \) are the temperature and salinity jumps across the mixed layer base, and \( K_T \) and \( K_S \) are the diffusivities of heat and salt below the mixed layer. \( F_{\text{sol}}, F_{\text{non}}, \) and \( F_{\text{salt}} \) will be discussed in more detail later in the paper. The entrainment velocity is defined to be equal to the rate of change of the mixed layer depth when the mixed layer is deepening:

\[
 w_e = \frac{\partial h_m}{\partial t} \quad \text{for} \quad \frac{\partial h_m}{\partial t} > 0 
\]

\[
 w_e = 0 \quad \text{for} \quad \frac{\partial h_m}{\partial t} < 0
\]

Thus changes in the mixed layer temperature and salinity are caused by exchanges with the atmosphere, sea ice, and the ocean below the mixed layer. The temperature and salinity below the mixed layer are determined from the following equations:

\[
 \frac{\partial T}{\partial t} = \frac{F_{\text{sol}}}{\rho c_p} \frac{\partial I(z)}{\partial z} + \frac{\partial}{\partial z} \left[ K_T \frac{\partial T}{\partial z} \right] 
\]

\[
 \frac{\partial S}{\partial t} = \frac{\partial}{\partial z} \left[ K_S \frac{\partial S}{\partial z} \right]
\]

The equation governing the evolution of the mixed layer depth, \( h_m \), is obtained from the turbulent kinetic energy budget of the mixed layer [e.g., Kraus and Turner, 1967], which includes the production of TKE by shear and buoyancy forces, the surface flux of TKE, and the dissipation of TKE. For this study, the formulation of Gaspar [1988] is used. The forcing terms that govern the evolution of \( h_m \) are the surface flux of mechanical energy, which is dependent on the friction velocity \( u_*, \) and the surface flux of buoyant energy, which is dependent on the heat and salinity fluxes \( F_{\text{sol}}, F_{\text{non}}, \) and \( F_{\text{salt}} \). The friction velocity is different under ice covered conditions than under open water conditions. Thus it is parameterized as:

\[
 u_* = (1 - A) u_{\text{ic}} + A u_{\text{at}} 
\]

where \( A \) is the fraction of open water contained in the ice pack in the form of leads, \( u_{\text{ic}} \) is the friction velocity under ice, and \( u_{\text{at}} \) is the friction velocity for the ocean which is in direct contact with the atmosphere. The ice/ocean relative velocity is assumed to be constant, and \( u_{\text{at}} \) is calculated as:

\[
 u_{\text{at}} = \frac{k (U_{\text{ic}} - U_{\text{ocean}})}{\ln \left( \frac{z_0}{z_{\text{ic}}} \right)}
\]

where \( k \) is the von Kármán constant equal to 0.4, \( U_{\text{ic}} - U_{\text{ocean}} \) is the relative velocity between the ice and ocean, \( z_{\text{ic}} \) is a depth in the ocean surface layer (taken to be 1 m), and \( z_0 \) is the roughness length at the bottom of the ice. Following Mellor and Kantha [1989], \( z_0 \) is set to 0.05 m for \( h_i \geq 3 \) m and linearly decreases to 0 m for \( h_i = 0 \) m. This assumes that the ridged ice has the same type of roughness elements as the multiyear ice. In reality, ridged ice will have a different shape as compared to undeformed ice, which may cause secondary circulations to arise, and will affect both the heat and momentum transfer between the ice and the ocean. However, observations of roughness lengths under ridged ice are sparse, and the incorporation of many of the effects of ridged ice requires significant changes in the current model. Some of these effects will be examined in future work.

### 2.3. Ocean/Sea Ice Interfacial Fluxes

The ocean and sea ice are coupled through the exchange of heat and fresh water. The heat flux into the mixed layer consists of a shortwave component \( F_{\text{sol}} \) and a turbulent component \( F_{\text{non}} \). Several processes contribute to the flux of fresh water into the mixed layer when sea ice is present. In addition to the fresh water inputs from advective processes and precipitation minus evaporation, the sea ice processes of...
ablation and accretion cause changes to occur in the mixed layer salinity. The freezing point of saltwater is lower than that of fresh water; thus when saltwater freezes, brine rejection occurs. Brine also drains out of the ice as it ages, leading to relatively fresh multiyear ice. Both these processes cause an influx of salt into the mixed layer. In contrast, sea ice ablation processes act to freshen the mixed layer.

2.3.1. Solar component of the heat flux. The shortwave heat flux into the ocean mixed layer is modified by the presence of ice. It consists of the shortwave energy which penetrates through the ice and/or enters the ocean through leads. Because of their relatively low albedo, the presence of melt water ponds on the ice surface modifies the amount of solar radiation which penetrates into the ocean mixed layer. The transmission of shortwave radiation through sea ice and into the upper ocean has been modeled by Ebert et al. [1995] using an ice thickness distribution model. Penetration of shortwave radiation through leads and into the ocean mixed layer has been modeled by Ebert and Curry [1993].

In the current model, the water in the lead is treated separately from the water in the ocean mixed layer. The lead water is defined as the region of the water column from the ocean surface down to the depth of the surrounding ice. Thus the shortwave energy that actually penetrates into the ocean mixed layer through the leads is that which penetrates deeper than the adjacent ice depth. When the net flux at the lead surface is positive, the heat is used for the lateral melting of the ice sheet and the warming of the water in the lead. Following Parkinson and Washington [1979], we set the fraction of the surface energy flux that is available to warm the water in the lead equal to the lead fraction. The remainder of the energy is used for lateral melting of the ice categories. Thus as the lead size increases, more energy goes directly into the water column. The sensitivities to this energy partition has been examined and found to be relatively minimal. Similarly, Harvey [1990] found that a thermodynamic sea ice model was relatively insensitive to changes in the lateral melting parameterization. When the surface heat budget of the lead is acting to cool the surface, all of the energy entering the lead is used to change the temperature of the water within the lead. If the lead water temperature drops below freezing, ice is grown vertically and latent heat release causes the temperature to return to the freezing point.

At the end of each time step, the lead water is mixed with the mixed layer water, resulting in a uniform mixed layer temperature and salinity. The role of the ice thickness distribution in determining the solar flux into the mixed layer is included in the following way. The value of $F_{\text{sol}}$ is determined by evaluating the term for each ice thickness category, and then area averaging to obtain the total amount of solar radiation which penetrates into the mixed layer.

2.3.2. Turbulent component of the heat flux. The turbulent component of the oceanic heat flux is obtained from the heat balance which occurs at the ice/ocean interface. This balance consists of the turbulent heat exchange between the ice and ocean, the conduction of heat at the ice base, and the latent heat flux due to ice ablation or accretion. It is obtained as follows:

$$F_{\text{NSOL}} + F_C - L_b \frac{\partial h_i}{\partial t} = 0$$  \hspace{1cm} (8)

where $L_b$ is the latent heat of fusion at the bottom of the ice slab which is a function of the brine volume of the ice and $\frac{\partial h_i}{\partial t}$, represents the rate of ice accretion or ablation at the base of the ice slab. $F_C$ represents the upward conductive heat flux at the bottom of the ice:

$$F_C = -k_i \frac{\partial T_i}{\partial z}$$  \hspace{1cm} (9)

where $k_i$ is the sea ice thermal conductivity and $T_i$ is the ice temperature.

The parameterization used here [McPhee, 1992] solves for the rate of ablation or accretion at the ice base and then calculates $F_{\text{NSOL}}$ from (8). It is assumed that the turbulent fluxes of temperature and salinity are proportional to the mean gradient of temperature and salinity, respectively. Integrating the turbulent flux equations from a depth $z$ to the surface results in

$$\frac{\rho c_p m_u}{\alpha_{\text{NSOL}}} [T(c) - T_0] = \Phi_T = \int_0^z \frac{u_z dz}{k_T}$$  \hspace{1cm} (10)

$$\frac{\alpha_s}{\alpha_{\text{STURB}}} \frac{S(c) - S_0}{S_0} = \Phi_S = \int_0^z \frac{u_z dz}{k_S}$$  \hspace{1cm} (11)

where $T_0$ and $S_0$ are the interfacial temperature and salinity, and $\Phi_T$ and $\Phi_S$ are nondimensional functions. $F_{\text{STURB}}$ is the turbulent salinity flux at the interface and is equal to

$$F_{\text{STURB}} = \left( w_i + w_o \right) \left( S_0 - S_i \right)$$  \hspace{1cm} (12)

where

$$w_0 = \frac{\rho \left[ \frac{\partial h_i}{\partial t} \right]}{\int_0^z \frac{h_i}{S} dz}$$  \hspace{1cm} (13)

represents the vertical velocity of the ice/ocean interface due to accretion or ablation at the base of the ice slab, $\rho$ is the density of the mixed layer, $\rho_i$ is the density of the ice, $S_i$ is the salinity of the ice, and $w_i$ is the "percolation" velocity of water which melts in the interior or at the surface of the ice column and migrates through the ice to the ice/ocean interface [McPhee, 1992]. The interfacial salinity is different from the mixed layer salinity and is not initially known. It is assumed that the interfacial temperature remains at the freezing temperature, and a linear freezing line approximation is used to relate the interfacial temperature to the interfacial salinity. This approximation and the mutual dependence of $F_{\text{NSOL}}$ and $F_{\text{STURB}}$ on the basal ice growth rate allows us to combine equations (10) and (11) in order to solve for the salinity at the ice/ocean interface. This gives the ice accretion or ablation rate at the ice base:

$$\frac{\partial h_i}{\partial t} = \frac{\rho}{\int_0^z \frac{h_i}{S} dz} \left[ \Phi_S \left( S_0 - S_i \right) \right]$$  \hspace{1cm} (14)

Because the conductive heat flux is known from the temperature profile of the ice slab, it is then possible to solve for the turbulent heat flux at the ice/ocean interface, $F_{\text{NSOL}}$, from (8).

$\Phi_T$ and $\Phi_S$ are parameterized following McPhee [1992] as a sum of a contribution across the transition/laminar sublayer plus a smaller component across the fully turbulent part of the boundary layer:

$$\Phi_{T,S} = \Phi_{\text{TURB}} + h_v \left[ \frac{u_z}{\alpha_{T,S}} \right] \frac{\alpha_{T,S}}{V}$$  \hspace{1cm} (15)

where $V$ is the kinematic molecular viscosity, $\alpha_{T}$ is the heat diffusivity, $\alpha_{S}$ is the salt diffusivity, and $h$ is a constant equal to 1.57. Because heat diffuses more quickly than salinity ($\alpha_T = 1.34 \times 10^{-5}$ m$^2$ s$^{-1}$ whereas $\alpha_S = 7.4 \times 10^{-10}$ m$^2$ s$^{-1}$), double-diffusive effects at the ice/ocean interface are possible in this formulation. $\Phi_{\text{TURB}}$ is the contribution of the fully turbulent part of the boundary layer and is obtained from similarity theory [McPhee, 1983]. It accounts for buoyancy effects under stabilizing (melting) conditions.
On the basis of the assumption that a certain amount of the surface runoff percolates through the ice as opposed to running off directly into the ocean through leads, \( w_i \) is parameterized to be a specified percentage (50\%) of the surface meltwater runoff. The sensitivity to this parameter has been tested and found to be relatively small. In determining the ice/ocean interfacial heat flux, the ice thickness distribution is explicitly accounted for by evaluating the flux locally under each ice thickness category. This involves using several category dependent variables, including the conductive flux at the ice base, the ice salinity, the amount of surface fresh water runoff, and the under ice roughness length and friction velocity. The turbulent heat flux is then weighted by the fractional area of each ice thickness category in order to obtain a single area-averaged \( F_{\text{nit}} \).

### 2.3.3. Surface fresh water flux

The flux of fresh water into the ocean mixed layer includes the effects of brine drainage from the ice as it ages (\( F_{\text{brine}} \)), ice ablation and accretion at the ice base (\( F_{\text{bottom}} \)), meltwater runoff from the ice surface (\( F_{\text{melt}} \)), fresh water inflow due to lateral advective processes (\( R \)), and precipitation and evaporation that affects the ocean directly through leads. The ice thickness distribution affects the fresh water flux because different ice categories have different rates of brine drainage and ablation and accretion.

When saltwater freezes, brine pockets become trapped in the ice, while the remainder of the saline water is flushed back into the ocean. The fresh water flux at the ice/ocean interface caused by the flushing of salinity (or fresh water) during ice accretion (ablation) is equal to

\[
F_{\text{bottom}} = (S_m - S_i) \rho_s \left( \frac{\partial h_i}{\partial t} \right)_b ,
\]

where \( S_i \) is the salinity of the ice in parts per thousand.

Brine pockets also form or enlarge when penetrating shortwave radiation causes ice to melt in the interior of the ice slab. As the ice ages, it becomes more porous and brine drainage occurs. This results in old ice having lower salinities than young ice. In the case when the ice thickness is increasing with age, the salinity of the ice is parameterized as a function of the ice thickness [Cox and Weeks, 1974; Ebert and Curry, 1993]:

\[
S_i = 14.24 - 19.39 h_i \quad h_i < 0.57 m
\]

\[
S_i = -3.2 \quad h_i \geq 0.57 m
\]

where \( h_i \) is in meters and \( S_i \) is in parts per thousand. The ice salinity is not allowed to increase with age, and thus if the ice thickness decreases with time, the salinity of the ice remains a constant. The brine that is flushed from the ice enters the ocean as a portion of the interfacial salinity flux:

\[
F_{\text{brine}} = \rho_s \left( \frac{\partial S_i}{\partial t} \right)_o .
\]

As the air temperatures warm during the summer, the snow cover and ice surface begin to melt. A specified fraction \( F_{\text{melt}} \) of the surface meltwater and precipitation is allowed to run off into the ocean either through leads or by percolating through the ice. The remainder of the surface meltwater is allowed to pool into ponds on the ice surface. The meltwater ponds affect the surface albedo and act as a latent heat reservoir in the autumn when the pond surface refreezes. The fresh water flux due to surface meltwater runoff is then

\[
F_{\text{melt}} = F_{\text{melt}} \left( S_m - S_i \right) \frac{\rho_s}{\rho} \left( \frac{\partial h_i}{\partial t} \right)_o + \left( S_m - S_i \right) \frac{\rho_s}{\rho} \left( \frac{\partial h_i}{\partial t} \right)_o .
\]

where \( \rho_s \) is the density of the snow, \( h_s \) is the snow thickness, \( P \) is the rate of precipitation in kilometers per meter squared per second and \( \frac{\partial h_i}{\partial t} \) is the rate of ablation at the ice surface.

The total salinity flux into the ocean mixed layer at the ice/ocean interface then equals

\[
F_{\text{salt}} = F_{\text{bottom}} + F_{\text{brine}} + F_{\text{melt}} + S_m \left[ A \left( E - P \right) - R \right] .
\]

The last term in the equation is the flux of salt due to precipitation (\( P \)) minus evaporation (\( E \)) in leads and fresh water advection (\( R \)). The fresh water advection includes the effects of river runoff and the influx of relatively fresh water through the Bering Strait. It has a simple half-period sinusoidal seasonal cycle that reaches a maximum during the summer. Climatological estimates of river runoff into the Arctic basin vary from 0.009 g m\(^{-2}\) s\(^{-1}\) to 0.016 g m\(^{-2}\) s\(^{-1}\) [e.g., Cattle, 1985], while estimates of the fresh water source due to the Bering Strait overflow are approximately 0.006 g m\(^{-2}\) s\(^{-1}\) [Aagaard and Carmack, 1989]. We set the annual average value for \( R \) in the baseline case to 0.020 g m\(^{-2}\) s\(^{-1}\). There are also fresh water fluxes into the Arctic Ocean of relatively saline water, notably from the North Atlantic. However, these do not influence the surface waters, and their effect on the deep ocean waters is taken into account indirectly in the model by fixing the temperatures and salinities at the base of the ocean model to climatological values. Additional sinks of fresh water directly affect the entire model domain and indirectly affect the ocean mixed layer. These include the export of relatively fresh ice and the diffusion of salt from the ocean depths, both of which are explicitly modeled. The fresh water balance for the model is discussed in more detail in the description of the baseline annual cycle.

### 2.4. Numerical Simulations

The values of parameters used for the baseline model simulation are given in Table 1. The model is integrated for a total of 100 years and is forced at the surface by an annual cycle of downwelling shortwave and longwave radiation fluxes, a constant surface wind speed, and the atmospheric temperature and humidity at a height of 2 m, following Ebert and Curry [1993] and part 1. A 100-year iteration length was chosen to insure equilibrium for the sensitivity tests. Precipitation values are obtained from the climatology of Vowinckel and Orvig [1970]. These values are multiplied by 1.6 to account for the gauge measurements, which underestimate the snowfall by about 60% [Ebert and Curry, 1993]. Evaporation from leads is calculated as a function of the latent heat flux at the lead surface. The ocean mixed layer depth can take any value. However, for the treatment of the ocean beneath the mixed layer a fixed resolution of 5 m is used. This results in a total of 40 levels, many of which fall within the mixed layer depth. The temperature and salinity at 200 m depth is set to the annual average values from AIDJEX. The sea ice model is run in the baseline case with 8 internal ice levels for each of 25 level and 15 ridged ice categories. The sensitivity to the number of level and ridged ice thickness categories is examined in part 1. The model is initialized for January 1 conditions. The initial ice thicknesses of the level ice are those of a normal distribution with thicknesses ranging from 0 to 8 m. No ridged ice is present in the initialized ice thickness distribution. However, the ridging process is active during most of the modeled year, and the ridged ice distribution reaches equilibrium around year 25. The initial area-averaged ice thickness is approximately 2.8 m.
Table 1. Baseline Parameters Used for the Model Simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of levels in the ice</td>
<td>$n$</td>
<td>8</td>
</tr>
<tr>
<td>Time step</td>
<td>$dt$</td>
<td>8 hours</td>
</tr>
<tr>
<td>Relative ice/ocean velocity</td>
<td>$U_{ic}$ - $U_{oc}$</td>
<td>4.0 cm s$^{-1}$</td>
</tr>
<tr>
<td>Surface friction velocity</td>
<td>$u_{fa}$</td>
<td>1.4 cm s$^{-1}$</td>
</tr>
<tr>
<td>Fraction of surface meltwater allowed to runoff</td>
<td>$f_{RO}$</td>
<td>0.85</td>
</tr>
<tr>
<td>Ocean diffusivity of heat</td>
<td>$K_h$</td>
<td>2.0 $10^{-5}$ m$^2$ s$^{-1}$</td>
</tr>
<tr>
<td>Ocean diffusivity of salt</td>
<td>$K_s$</td>
<td>2.0 $10^{-5}$ m$^2$ s$^{-1}$</td>
</tr>
<tr>
<td>Fraction of total ice area exported from the model domain</td>
<td>$e$</td>
<td>0.13 yr$^{-1}$</td>
</tr>
<tr>
<td>Maximum number of level ice categories</td>
<td>$n_{lv}$</td>
<td>25</td>
</tr>
<tr>
<td>Maximum number of ridged ice categories</td>
<td>$n_{ri}$</td>
<td>15</td>
</tr>
<tr>
<td>Average value of the fresh water advection</td>
<td>$R$</td>
<td>0.020 g m$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Fraction of surface runoff that percolates through the ice</td>
<td>$w_{f}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

3. Simulation of the Annual Cycle

In this section the simulated annual cycles of ocean mixed layer characteristics and ice/ocean interfacial fluxes are examined. In these simulations a separate ice/ocean flux is determined locally beneath each ice thickness category. The baseline simulation is examined in order to explore the physical processes that are active in the ocean mixed layer/sea ice system. Simulated mixed layer salinity, temperature and depth are compared to observations from AIDJEX. In determining the mixed layer properties from AIDJEX data, it was assumed that the mixed layer base occurred at the shallowest depth for which a significant change in density with depth occurred. The mixed layer temperature and salinity values were then computed as the average values of temperature and salinity within the mixed layer. AIDJEX observations were taken from ice drifting stations and are point measurements which include the effects of advection. These stations passed over ocean fronts into different water masses, causing rapid changes to occur in the observed temperature and salinity structure of the ocean [Mayhut and McPhee, 1995]. The ice/ocean model presented here represents a drifting parcel of ice under average Arctic conditions at approximately 80$^\circ$N. It parameterizes some advective effects such as river inflow and ice divergence. These parameterizations are based on climatological averages. Thus we do not expect that the model results will correspond exactly to the AIDJEX data. However, we hope to show that the model results are reasonable based on the range of variability observed during AIDJEX.

The annual cycles of the ice thickness distribution and ice surface properties for the baseline model run are described in detail in part 1. The annual area-averaged ice thickness for the baseline simulation is approximately 3.03 m, which agrees relatively well with the generally accepted average Arctic sea ice thickness of 3 m [e.g., Bourke and Garrett, 1987]. On an annual average, the multiyear ice occupies approximately 38% of the area, whereas the first-year ice, ridged ice, and leads account for approximately 18%, 40%, and 4% of the area, respectively. The areal percentages of the first-year and multiyear ice categories as well as the leads vary significantly over the course of the year, while the ridged ice fraction remains relatively constant. During the melt season the lead fraction increases to a maximum of approximately 21% by late August. The increased lead fraction is compensated by a decrease in the first-year, multiyear, and, to a lesser extent, the ridged ice fractions. In early September the leads freeze over and become first-year ice. The relative fractions and interplay between multiyear ice, first-year ice, and leads have important effects on the fluxes of heat and salinity into the oceanic mixed layer, as will be shown in the following sections.

3.1 Mixed Layer Salinity

The annual cycle of the mixed layer salinity is shown in Figure 2. Also shown are the monthly averaged mixed layer salinity values determined from AIDJEX salinity profiles. There are some differences in the mixed layer salinities of the four drifting AIDJEX ice stations. The simulated mixed layer salinity corresponds very well from August through April with

![Figure 2. Annual cycle of the simulated mixed layer salinity. The monthly averaged data from the four AIDJEX drifting ice stations are also shown.](image-url)
the values from AIDJEX station Snow Bird. A sharp decrease in the AIDJEX mixed layer salinity at all camps is observed between the April and May monthly averages. The data from the AIDJEX stations is present from May, 1975 through April, 1976 for camps Blue Fox, Snow Bird and Caribou. Station Big Bear was present from April, 1975 until October, 1975. Thus the sharp change in ocean mixed layer properties that appear from April to May in the plotted data is a result of the different years and locations from which the data was obtained. The model is not forced with AIDJEX meteorological data, and the dynamic forcing present in the model remains unrealistically constant throughout the year, although ridging ceases when the open water fraction becomes larger than 5%. Thus the differences between the modeled mixed layer salinities and those observed during AIDJEX appear reasonable on the basis of the different forcing that is present.

From early May until early November the fluxes at the ocean surface act to freshen the mixed layer. However, because of a relatively saline ocean beneath the mixed layer, diffusion and entrainment from the deeper ocean act to salinize the mixed layer throughout the year. The combined effect of the fresh water fluxes from the surface and the deeper ocean causes the mixed layer to freshen for a relatively short time from mid-May to mid-August (Figure 3a). The mixed layer salinity exhibits its most rapid changes during July. This is largely due to the effect of surface melt runoff (Figure 3b) which is only nonzero from late June to early August. Fluxes due to bottom ablation, fresh water advection, lateral melting in leads, and precipitation into leads also contribute to the summertime freshening of the mixed layer in decreasing importance. During the remainder of the year the changes in the mixed layer salinity are more gradual and act to salinize the mixed layer. This salinization is caused both by the salinity flux at the mixed layer base and by the brine rejection and drainage that occurs at the ocean surface during bottom ice accretion and ice aging (Figure 3b).

The ice thickness distribution plays an important role in determining the mixed layer salinity. Thin first-year ice produces a disproportionately large amount of the total basal accretion during the winter months and thus contributes approximately 63% of the winter brine rejection and drainage, although it occupies only 18% of the area. The presence and rapid growth of thin first-year ice is largely responsible for the increase in mixed layer salinity that occurs during the wintertime months. The summertime processes that act to freshen the mixed layer are less dependent on ice thickness.

The mixed layer salinity is also indirectly affected by processes that influence the fresh water balance of the entire model domain. The divergence of ice and snow acts as a fresh water sink as does the diffusion of salt from the deep ocean into the water column. In the baseline simulation, net divergence accounts for a fresh water loss of 0.1 m yr$^{-1}$ and deep ocean diffusion for a loss of 0.3 m yr$^{-1}$. Ice divergence affects the mixed layer salinity by allowing the creation of open water, which results in high basal accretion and brine rejection rates. Salinity diffusion from the deep ocean causes the water column to be more saline in general; this salinity can then be entrained or diffused into the ocean mixed layer. These processes are largely balanced by the fresh water advection term ($K$) which represents river runoff and Bering Strait overflow and causes 0.6 m yr$^{-1}$ of freshening. To a lesser extent, precipitation minus evaporation acts as a net fresh water source (0.1 m yr$^{-1}$). The values obtained and prescribed in the model simulated fresh water balance are in general agreement with values cited in the literature [e.g., Aagaard and Carmack, 1989; Cattle, 1985].

### 3.2. Mixed Layer Temperature

The mixed layer temperature is shown in Figure 4. The simulated values correspond relatively well with the monthly averaged mixed layer temperatures observed during AIDJEX. The wintertime temperatures generally remain at their salinity-determined freezing point. As was previously mentioned, the AIDJEX drifting ice stations were present from May, 1975 through April, 1976. The discontinuity in the observations from April to May causes a sudden decrease in mixed layer salinity to occur. This results in an increased freezing temperature, which accounts for the decrease in AIDJEX mixed layer temperature from April to May. Similar effects are not seen in the modeled mixed layer temperature owing to the neglect of explicit oceanic advection. However, in general, the modeled mixed layer temperature follows a pattern similar to that of the AIDJEX observations and elevates above the freezing point by a similar amount during the summer months.
The elevation of mixed layer temperature above the freezing point at this time is largely due to penetrating solar radiation.

The annual cycle of the components of the heat flux into the mixed layer is presented in Figure 5. The mixed layer heat budget includes the effects of penetrating solar radiation, the ice/ocean interfacial turbulent heat exchange, the latent heat flux due to frazil ice formation, the heat entrained and diffused into the mixed layer from the deeper ocean (not shown), and the fraction of the flux of heat into the lead water that is used for warming the ocean water (as opposed to lateral melting). During the summer months the total flux of heat into the mixed layer is essentially a competition between the turbulent heat loss at the ice/ocean interface and the solar flux penetrating through leads and ice which acts to warm the mixed layer. The flux of heat into the leads is substantial during these months. However, the majority of this flux is used for the lateral melting of the ice sheet surrounding the lead. At the end of the melt season when a significant fraction of open water is present and the atmospheric fluxes begin to cool the surface, the lead water is strongly cooled, resulting in large negative heat fluxes through the leads. After these large open water fractions have frozen over, the ocean is insulated more efficiently from this strong atmospheric cooling, and the lead flux remains at a relatively small negative value.

During the winter months the latent heat released during frazil ice formation balances the ocean heat that is lost due to turbulent exchange. The mixed layer remains at the salinity-determined freezing point during this time. The salinity at the ice/ocean interface is higher than that of the ocean mixed layer as a result of the basal accretion which is occurring (Figure 6). Thus the temperature at the interface, which remains at the freezing point, is lower than that of the mixed layer. Because heat diffuses more quickly than salinity, this causes nonzero turbulent heat fluxes to occur throughout the year. This results in a supercooling of the ocean mixed layer and the production of frazil ice within the water column. The flux of heat at the mixed layer base due to entrainment and diffusion has a

**Figure 4.** Annual cycle of the simulated mixed layer temperature. The monthly averaged data from the four AIDJEX drifting ice stations are also shown.

**Figure 5.** Annual cycle of the components of the flux of heat into the ocean mixed layer. Positive fluxes warm the ocean.

**Figure 6.** Annual cycle of the ice/ocean interfacial (a) salinity and (b) temperature for first-year (FY) ice, multiyear (MY) ice, and ridged (RI) ice. Also shown are the mixed layer salinity and temperature.
relatively small effect as compared to the other ocean heat fluxes and is not shown in Figure 5. It remains positive throughout the nonsummer months and reaches a monthly averaged maximum of 0.9 W m$^{-2}$ in September. During the summer it decreases to negative values as the diffusion of heat across the mixed layer base acts to cool the mixed layer. This supports the hypothesis put forth in several studies [e.g., Maykut and McPhee, 1985; Maykut, 1987] that the penetration of solar radiation into the ocean mixed layer, rather than the diffusion or entrainment of warm water from below, is the dominant factor in determining the size of the basal heat flux. It is likely that if variable winds and ice/ocean velocities were used in the model simulation, the entrainment of heat into the mixed layer would be modified. However, preliminary studies of the effect of variable forcing in the model show that although the entrainment of heat is modified somewhat in the summer, penetrating solar radiation is still the dominant factor in the summer warming of the mixed layer.

The turbulent heat flux is highly dependent on the ice type under which it occurs, and the sharp increase in the magnitude of the area averaged turbulent heat flux at the end of the melt season is caused by the formation of large amounts of thin first-year ice when the lead fraction freezes over. The magnitude of the turbulent flux is largest under first-year ice, averaging approximately -11.8 W m$^{-2}$ annually, whereas the multiyear ice and ridge ice annually averaged turbulent heat fluxes are -6.3 and -4.8 W m$^{-2}$, respectively. Based on the roughness lengths of the different ice types, this result appears to be counterintuitive, since rougher ice would have a larger turbulent heat exchange associated with it. However, the increased turbulent heat flux under thinner ice is largely due to the previously mentioned double diffusion effects which occur during the winter months. First-year ice has a relatively large wintertime basal ice accretion and brine rejection. Because salinity diffuses slowly compared to heat, the interfacial salinity remains larger under first-year ice (Figure 6). This results in a relatively low freezing temperature, which causes a larger difference to occur between the wintertime mixed layer temperature and the freezing temperature at the base of the first-year ice. Thus a relatively large heat flux at the first-year ice/ocean interface occurs during the winter. The basal heat flux under multiyear and ridge ice is nearly zero during winter.

The flux of solar energy into the mixed layer is also highly dependent on the simulated ice thickness distribution, particularly the lead and first-year ice fractional areas (Figure 7). The majority of the solar flux into the upper ocean, approximately 73% of the annual average, penetrates through leads. However, during the spring and autumn months, when the lead fraction is relatively small, the solar energy flux into the mixed layer is composed almost entirely of shortwave energy penetrating through first-year ice. This energy contributes 24% of the annual average. The energy transmitted through multiyear and ridge ice contributes the remaining 3% and is present only in mid-summer when the ice is snow free and the ice thickness is at a minimum.

3.3. Mixed Layer Depth

The annual cycle of the mixed layer depth is shown in Figure 8, along with the observations from AIDJEX. The mixed layer depth is forced by mechanical stirring and buoyancy effects. The mechanical forcing represented by the friction velocity is nearly constant throughout the nonsummer months, since the lead fraction is minimal during this time and the wind, ice, and ocean speeds are assumed to be constant. Thus most changes in the mixed layer depth occur as a result of buoyancy forcing. As is illustrated by the figures of salinity flux, during the spring, winter, and fall months the mixed layer becomes more saline as a result of brine rejection and drainage due to ice accretion and aging. This leads to a denser, unstable mixed layer and enhances the turbulent activity in the mixed layer, causing it to deepen to a maximum depth of 59 m in mid-May. During the melt season, fresh water enters the mixed layer, and the mixed layer warms owing to the flux of solar radiation. This stabilizes the water column and causes the mixed layer depth to retreat, reaching a minimum of approximately 17 m in mid-July. During this time, turbulent mixing is maintained by mechanical stirring due to the wind and relative movement of the ice cover.

The modeled mixed layer depth decreases sharply during the month of May, which is approximately a month earlier than that observed during AIDJEX. The simulated decrease in mixed layer depth coincides with the date at which the net fresh water flux into the ocean mixed layer becomes positive. At this time, basal accretion is occurring, causing a salinization of the mixed layer. However, a net freshening of the mixed layer occurs due to river runoff and Bering Strait inflow. These fresh water sources have a highly parameterized seasonal cycle. Using different seasonal cycles of fresh water inflow with the same annual average value, it is possible to delay the date of mixed layer depth retreat. For example, using an inflow seasonal cycle that is negligible throughout the spring and peaks in mid August, the mixed depth retreat begins 25 days later than in the baseline simulation. In addition, variable winds and ice/ocean relative velocities appear to be important for driving the mixed layer dynamics [e.g., Lenke et al., 1990]. Thus the neglect of variations in the winds and ice velocities is likely to be responsible for some of the discrepancy between the modeled and observed mixed layer depth. Preliminary studies of the effects of variable velocities in the model simulation show differences in the ice/ocean state. However, the summertime retreat of the ocean mixed layer occurs at approximately the same time. Further studies
Figure 8. Annual cycle of the simulated mixed layer depth. The monthly averaged data from the four AIDJEX drifting ice stations are also shown.

are underway to determine the effect of variable forcing on the ice/ocean interactions and mixed layer dynamics.

4. Sensitivity of Ice/Ocean Interactions to the Ice Thickness Distribution

As shown by previous studies, the ice pack is very sensitive to values of the ice/ocean interfacial turbulent heat flux [e.g., Maykut and Untersteiner, 1971, Seminler, 1976, Harvey, 1986]. In calculating the ice/ocean interfacial heat balance, the ice thickness distribution is taken into account explicitly by computing a different heat balance for each ice category. Category specific ice conditions, such as the conductive flux at the base of the ice, are used in these calculations. To assess the importance of the ice thickness distribution in determining the interfacial heat balance, two different studies are conducted. The first of these compares the baseline simulated interfacial heat balance to the balance obtained using different ice thickness distributions. The second study compares the baseline simulation with a simulation in which average ice conditions are used to compute the ice/ocean interfacial heat balance.

4.1. Interfacial Heat Balance Under Different Ice Thickness Distributions

In this study we examine the interfacial heat balance that results from three different ice thickness distributions. These include the baseline simulation described above, a single ice thickness category that represents a uniform slab of ice, and an imposed seven category distribution. The average ice thickness used to obtain the single category distribution is the same as that obtained in our baseline simulation. The imposed seven-category distribution considers ice categories which range in thickness from 0.1 m to twice the average ice thickness obtained in the baseline simulation. These are equally spaced about the average ice thickness following Hibler [1984]. Thus an ice/ocean interfacial heat balance is computed for seven ice categories with thicknesses at every $h_i$, where $h_i$ is the baseline average ice thickness. The interfacial heat balance is determined for both the single-category and seven-category ice thickness distributions diagnostically whereby the baseline ice and ocean characteristics are used in the calculations. This allows us to isolate the effects that the ice thickness distribution has in determining the interfacial heat fluxes. The flux values determined using these imposed distributions are not applied in the model simulation.

The area averaged ice/ocean interfacial heat flux and resulting changes in ablation and accretion at the ice base are shown in Table 2 for the baseline ice thickness distribution, the single-category distribution, and the imposed seven-category distribution. The presence of an open water category in these distributions is possible but does not affect the results obtained here since we are only examining the ice/ocean interfacial heat flux and the basal ice growth rates. Differences between the thickness distribution computations exist year-round. The single ice category conditions result in decreased heat loss from the ocean to the ice. About half as much basal ice growth occurs during the winter months as compared to the baseline simulation. During the summertime, the single-category conditions cause a substantial decrease in basal melting. In contrast, compared to the baseline simulation, slightly more basal ablation occurs in the summer months and more basal accretion occurs during the remainder of the year in the presence of the seven-category distribution. The relative amounts of thin ice in the different distributions are largely responsible for the different basal heat flux and ablation/accretion rates which are obtained. When a single ice category is used, the absence of relatively thin ice causes the ocean to be more efficiently insulated from the atmosphere. This causes decreased ice growth at the ice/ocean interface when the atmosphere has a large cooling effect and decreased basal melting when the atmosphere is warming the ice cover. In the case of the seven-category distribution, each category is given an equal weight or area, whereas in the baseline simulation an ice thickness distribution with a single peak near the multiyear ice thickness is present [part 1]. Thus, a relatively large amount of thin ice is present in the seven category simulation, causing a smaller insulating effect to occur. This results in the relatively large basal accretion and basal ablation rates. If we used a seven-category distribution which was more similar in shape to that obtained in our baseline simulation, the computed interfacial heat balance would compare more favorably. However, under climate change scenarios, the shape of the thickness distribution will

| Table 2. Area Averaged Basal Heat Flux for the Melt and Growth Seasons and the Values of Basal Ablation and Accretion for the Baseline Ice Thickness Distribution, a Single-Category Distribution, and an Imposed Seven-Category Distribution |
|-----------------|---------|---------|---------|
|                  | Baseline | Single | Seven   |
| Base ablation    | 0.32     | 0.16    | 0.33    |
| Base accretion   | 0.32     | 0.14    | 0.47    |
| Base Heat Flux   |          |         |         |
| Warm season      | 11.68    | 6.76    | 12.30   |
| Cold season      | 4.46     | 2.55    | 5.02    |

Baseline heat flux values are in watts per meter squared. Basal ablation and accretion rates are in centimeters per day.
likely change from what is presently observed. Thus while imposing a “present-day” distribution in determining ice growth rates will likely give relatively good model results for the present climate, it will not necessarily provide better results than a single-ice-category model when issues of climate change are examined.

### 4.2. Interfacial Heat Balance Computed and Applied Using Average Ice Conditions

In this section, results from the baseline simulation are compared to results from a simulation in which area-averaged ice conditions are used to compute the ice/ocean interfacial heat balance. The use of area-averaged ice conditions results in a single basal ice ablation/accrretion rate which is applied for each ice category in the simulation. Table 3 shows the mass balances obtained for the two simulations. More details on the ice mass balance are presented in part 1. The annual area-averaged ice thickness is approximately 2 m greater for the average ice condition case. This is a consequence of the relatively large basal ice growth that is obtained in this simulation.

During the nonsummer months, the balance of fluxes at the ice/ocean interface results in the accretion of ice from early September to early June. The magnitude of the conductive heat flux in the winter is highly dependent on the thickness of the ice, with the flux being significantly larger for thinner ice as a result of strong surface cooling. In the baseline simulation, this leads to a first-year ice basal accretion (3.1 m yr⁻¹) that is over 5 times as large as that of the multiyear ice (0.6 m yr⁻¹). Much of the first-year ice becomes ridged or exported, allowing the first-year ice thickness to remain relatively thin. In the average ice condition case, the average conductive heat flux is used in (8) to compute the balance of fluxes at the ice/ocean interface. This results in equal amounts of accretion for first-year and multiyear ice. Thus, less accretion occurs on the first-year ice and more accretion occurs on the multiyear ice, resulting in thin first-year ice (0.64 m) and thick multiyear ice (5.74 m) as compared to the baseline simulation values of 0.82 m and 1.60 m, respectively.

Although the average ice thickness is significantly thicker in the average condition case, the average conductive heat flux is larger during the winter, equaling 21 W m⁻² as compared to the baseline value of 15 W m⁻². This is caused by the presence of relatively thin first-year ice in the average condition case.

In order to balance these relatively large conductive fluxes, the total basal ice growth, which includes basal accretion and frazil ice formation, is 0.38 m greater than in the baseline simulation (Table 3). For the average condition simulation, a mass balance is obtained in which larger ice production rates are balanced by an increased amount of ice export and lateral melt. The relatively large ice production results in relatively thick ice, whereas the increased export and lateral melt rates are a consequence of the thicker ice which is present.

Clearly, the ice thickness distribution is an important factor in determining the magnitude of the interfacial heat flux balance. Thin ice produces a disproportionately large conductive flux during the winter, which if taken into account results in a relatively large accretion rate at the ice base. This appears to be the most important factor in determining the ice/ocean interfacial heat flux balance and the resulting ice mass balance. Other category dependent characteristics, such as the ice roughness length, have a significantly smaller effect. Thus, it appears that the consideration of the ice thickness distribution, and in particular the category-varying conductive fluxes, is essential to accurately model the ice/ocean interfacial heat exchange.

### 5. Basal Heat Flux Parameterization Comparison

In order to examine the physical mechanisms that are important for the interfacial ice/ocean heat exchange, four different parameterizations of basal heat flux are used in the model and the results are compared. The four model simulations are run from the same initial conditions with the differently parameterized interfacial heat balances applied at each time step and under each ice category. Parameterization I is that used in the baseline simulations [McPhee, 1992]. This parameterization accounts for the stabilizing effect of meltwater runoff on ice/ocean turbulent heat exchange and allows for molecular sublayer effects, including different molecular diffusivities for temperature and salinity. Because temperature diffuses more quickly than salinity, this allows double diffusion to occur at the ice/ocean interface. In order to examine these effects, parameterization II is the same as that described above but neglects double diffusion by setting the diffusivity of salinity ($\alpha_S$) equal to that of temperature ($\alpha_T$). This causes salinity to diffuse more rapidly than it does in reality and results in lower interfacial salinity values under thin ice during times of basal accretion. Parameterization III is a simplified formulation [Mayak et al., 1995]:

$$F_{NSOL} = \rho c_p c_p h m \cdot \bar{a} \cdot T_n - \bar{a} \cdot T_f$$  \hspace{1cm} (21)

where $c_p$ is the heat transfer coefficient which is set equal to a constant (0.006). This parameterization does not account for molecular sublayer or surface buoyancy effects. The last parameterization used in this comparison, parameterization IV, follows Fichefet and Gaspar [1988]. It does not allow for any heat storage within the ocean mixed layer, causing the ocean mixed layer temperature to remain at the salinity determined freezing point. This constraint on ocean mixed layer temperature allows us to solve (1) for the interfacial heat flux:

$$F_{NSOL} = \rho h m \left[ \frac{\partial T_f}{\partial h} + w e \Delta T + K_n \frac{\partial T}{\partial z} \right] - F_{SO} \left[ 1 - \left( -h_m \right) \right]$$  \hspace{1cm} (22)

| Table 3. Mass Balance for the Two Different Cases of Interfacial Heat Flux Parameterization |
|-----------------------------------------------|----------------|
| **Baseline** | **Average Ice Conditions** |
| Average thickness, m | 3.03 | 4.98 |
| Surface ablation, m | -0.21 | -0.21 |
| Bottom ablation, m | -0.30 | -0.32 |
| Lateral ice melt, m | -0.21 | -0.30 |
| Ice export, m | -0.42 | -0.70 |
| Bottom accretion, m | 0.86 | 1.07 |
| Frazil ice, m | 0.21 | 0.38 |
| Growth in leads, m | 0.07 | 0.07 |
Thus any heating of the mixed layer due to penetrating solar radiation or entrainment and diffusion at the mixed layer base is balanced by turbulent exchange at the ice/ocean interface. This results in a time-varying heat flux that is the same under every ice category.

The mass balance and annually averaged ice thickness for the four different simulations are presented in Table 4. The basal heat flux has a direct effect on the ice mass balance through the amount of basal ablation and accretion which occurs. The baseline simulation which uses parameterization I obtains the thickest annually area averaged ice cover. The use of parameterizations II, III, and IV causes reductions in annual average ice thickness relative to the baseline simulation of 0.09 m, 0.01 m and 0.25 m respectively. Simulations which obtain thinner average ice covers generally result in fresher mixed layer salinities and allow more solar radiation to penetrate into the ocean.

The average growth at the base of the ice, which includes basal accretion and frazil ice production, ranges from 1.04 to 1.11 m yr\(^{-1}\) for the four different simulations. These differences are largely caused by changes in the simulated ice thickness distribution. Thin ice insulates the ocean less efficiently, and thus cases with generally thinner ice result in increased basal accretion. In contrast to the other cases examined, parameterization I calculates 0.21 m yr\(^{-1}\) of the average basal ice growth as frazil ice production. In the model, this particular form of ice growth is caused by the supercooling of the ocean mixed layer and is spread equally over the different ice categories. In contrast, basal accretion is highly dependent on the ice thickness category under which it occurs. The different partitioning of ice growth between frazil and basal ice accretion causes significant differences to occur in the ice thickness distribution. Frazil ice formation is present in parameterization I because double-diffusive effects are accounted for at the ice/ocean interface. During the winter the ice is freezing at the base and thin ice is experiencing very rapid growth. This causes a large amount of brine rejection to occur under the thin ice categories. This high salt rejection and the relatively slow diffusion of salinity results in high salinity values under thin ice when using parameterization I. Because the interfacial and mixed layer temperatures generally remain at their salinity-determined freezing points during this time, relatively large differences in temperature result. This causes large (up to 27 W m\(^{-2}\)) interfacial heat fluxes to occur under thin ice during the winter months. This reduces the amount of thin ice basal accretion, causes a supercooling of the ocean mixed layer, and results in the formation of frazil ice.

Although observations of frazil ice production in the Arctic are lacking, the amount of frazil ice produced with parameterization I may be unreasonably high. Basal heat flux parameterization I contains the most physical processes of those examined. It is likely that these processes are accurate but that the frazil ice production simulated due to the high growth rates of relatively thin ice may occur in a localized region near the particular ice type. This frazil ice production would then act in the same way as basal freezing and would preferentially accrete onto thin ice types. However, the relative ice/ocean velocity will likely affect the depth at which the frazil ice formation occurs and the ice type onto which it accretes. More observations are needed to determine the influence of large basal accretion rates on the calculation of the wintertime basal heat flux, double-diffusive effects at the ice/ocean interface, and the rates of frazil ice formation and settling.

Basal ablation varies by approximately 0.11 m between the four cases, with the largest value (0.38 m yr\(^{-1}\)) being obtained when parameterization IV is used. Parameterization IV allows no ocean mixed layer heat storage to occur. Thus all heat entering the mixed layer is lost at the ice/ocean interface, resulting in relatively high basal ablation rates. This causes thinner ice to occur and allows more solar radiation to penetrate into the mixed layer, which in turn causes still higher interfacial heat exchange and basal ablation rates. This is largely responsible for the reduced ice thickness which is present when parameterization IV is used. The relatively minor differences in basal ablation present for simulations using parameterizations I, II, and III are caused by differences in the amount of solar radiation absorbed and heat stored in the ocean mixed layer.

Figure 9 shows the elevation of the ocean mixed layer temperature above the freezing point for the four cases. The simulation using parameterization I has a relatively low amount of penetrating solar radiation but obtains the largest elevation of mixed layer temperature. This parameterization accounts for the stabilizing effects of meltwater on the ice/ocean interfacial turbulent exchange as well as for double-

| Table 4. Annual Area-Averaged Ice Thickness and Ice Mass Balance in Meters for the Four Different Turbulent Heat Flux Parameterizations Considered |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Process                        | Parameterization I | Parameterization II | Parameterization III | Parameterization IV |
| Ice thickness                  | 3.03 m           | 2.94 m           | 3.02 m           | 2.78 m          |
| Surface melt                   | -0.21 m          | -0.21 m          | -0.22 m          | -0.21 m         |
| Basal ablation                 | -0.30 m          | -0.33 m          | -0.27 m          | -0.38 m         |
| Lateral ice melt               | -0.21 m          | -0.20 m          | -0.19 m          | -0.20 m         |
| Ice export                     | -0.42 m          | -0.41 m          | -0.42 m          | -0.39 m         |
| Basal accretion                | 0.86 m           | 1.09 m           | 1.04 m           | 1.11 m          |
| Frazil ice                     | 0.21 m           | 0.00 m           | 0.00 m           | 0.00 m          |
| Growth in leads                | 0.07 m           | 0.06 m           | 0.06 m           | 0.07 m          |

Parameterization I refers to the baseline parameterization, parameterization II is identical to parameterization I except that it neglects double diffusive effects, parameterization III is a simple drug law formulation, and parameterization IV neglects heat storage in the ocean mixed layer.
Figure 9. Elevation of the mixed layer temperature above freezing for the four different basal heat flux parameterizations considered.

diffusion effects at the interface. Both these effects act to decrease the turbulent heat loss from the ocean mixed layer during times of fresh water input from ice melt. This allows the ocean mixed layer to store a greater amount of heat and causes a higher elevation in mixed layer temperature to occur. Parameterization II contains the same physics as parameterization I except that it neglects double-diffusive effects. This causes a decrease in the mixed layer temperature elevation as compared to the baseline simulation. Thus it appears that double diffusion at the ice/ocean interface is important for determining the interfacial heat flux and the ocean mixed layer heat storage during the summer months. Parameterization III calculates a slightly smaller elevation of ocean mixed layer temperature as compared to parameterization I.

Although parameterization III has relatively simple physics and does not consider the stabilizing effect of meltwater or double-diffusive effects, it has results very similar to those obtained in the baseline simulation. Thus it appears that this simplified parameterization provides reasonably good agreement with the more complete physics of parameterization I. In order to test whether parameterization III would provide accurate results under climate perturbation scenarios, surface longwave warming perturbations of 3, 10, and 15 W m⁻² were applied in model simulations using the four different basal heat flux parameterizations. The warming perturbations were applied at every time step and the simulations were run to equilibrium. The annual area-averaged ice thickness obtained in the perturbation experiments for simulations using the four different basal heat flux parameterizations are shown in Figure 10. The modeled ice thickness response to the longwave warming perturbations is very similar in cases using basal heat flux parameterizations I, II, and IV. In contrast, the simulation using parameterization III obtains a significantly larger decrease in average ice thickness with increased warming. For the warming perturbations, more relatively fresh surface meltwater is entering the ocean mixed layer, and the stabilizing effect of meltwater and double diffusive effects will likely be more important. The simplified physics present in parameterization III is unable to account for the changes in the ice mass balance which are caused by these effects. Thus although tuning of the heat transfer coefficient provides a reasonable present day simulation, larger errors are obtained under perturbation scenarios.

6. Discussion and Conclusions

Previous studies have examined ice/ocean interactions in the context of a ocean mixed layer model coupled to a sea ice model in which open water and a single ice thickness exist [e.g., Pollard et al., 1983; Fichefet and Gaspar, 1988; Mellor and Kantha, 1989]. Additionally, the effect that the ice thickness distribution has on determining the fluxes between the ice and ocean has been studied in the absence of an interactive ocean mixed layer [e.g., Maykut, 1982; Maykut and McPhee, 1995]. The current study differs from this previous work in that we explicitly model the coupled ice thickness distribution/ocean mixed layer system. This study has been presented with particular attention to the sea ice/ocean interactions and the effect of the ice thickness distribution on the ice/ocean coupling. The model incorporates sophisticated parameterizations of sea ice thermodynamic processes and an ice thickness distribution that includes an export and ridging parameterization. A bulk ocean mixed layer model, which assumes that the mixed layer properties are constant across the mixed layer depth, is included. The ocean and sea ice are coupled through the exchange of heat and fresh water. The ice thickness distribution plays an important role in determining this coupling.

The model produces a seasonal cycle of ice and mixed layer properties that are in reasonable agreement with the data that is available. The modeled results of the ocean mixed layer have been compared with oceanic data from AIDJEX. Although the advective heat and salt fluxes are not included in this data set, it has been inferred that advection played a prominent role in determining the mixed layer characteristics during AIDJEX. The model does not explicitly include horizontal advection in the ocean mixed layer, although there is a term for freshwater input associated with river and Bering Strait inflow. To unambiguously interpret the heat and salt budgets of the ocean.

Figure 10. Annually area-averaged ice thickness obtained as a function of longwave heat perturbation for the four different basal heat flux parameterizations considered.
mixed layer, the effects of horizontal advection must be
accounted for explicitly. The differences between model
simulation and observations arise either from differences in the
forcing, deficiencies in the modeled ice/ocean exchange, or the
neglect of advective processes. The observational data base
for the Arctic is sparse both spatially and temporally. More
observations are needed to validate and improve models of the
type presented here. It is believed that the Surface Heat Budget
of the Arctic Ocean Experiment [SHEBA Science Working
Group, 1994] will provide accurate data that will be extremely
useful in the study of ice/ocean interactions.

The ice thickness distribution is important for the exchange
of both heat and salt between the ice and the ocean. This is
especially true with respect to the effects of thin first-year ice.
During the nonsummer months, thin ice accounts for a
disproportionately large amount of the basal ice accretion and
salinity flux into the mixed layer. This is due to the fact that
thin ice is a relatively inefficient insulator of the ocean, causing
large accretion rates to occur during the winter. The increased
accretion rate under relatively thin ice causes a large
salinity flux due to brine rejection. The leads and first-year ice
have a large effect on ice/ocean exchange in the summer
months by allowing solar radiation to enter the ocean. This
leads to a warmer ocean mixed layer and causes a higher
turbulent heat exchange at the ice/ocean interface during the
summer. The modeled effect of the ridged ice on the ice/ocean
interfacial processes is relatively minimal. In essence, it acts
like thick, multiyear ice. However, it appears that the pressure
keels have an important effect on the ice/ocean exchange of
momentum [Steele et al., 1989] and are also likely to have a
large influence on heat and salt exchange. Thus ridged ice may
play an important role in ice/ocean interactions. Because of
the simplified parameterization of the ridging process and the
lack of advection in the model, this role is not clear in our
model simulations.

Ice-ocean interfacial flux parameterizations that do not
explicitly allow interactions with the ice thickness
distribution will not reproduce the correct exchange of heat
and salt between the ice and the ocean. In addition, models that
ignore the variability of the ice on small spatial scales or
impose an "externally specified" ice thickness distribution
may produce reasonable present-day simulations but will not
accurately simulate the sea ice and ocean mixed layer response
to varying model parameters or perturbations of the forcing.
Because of the complexity of the ice thickness distribution, it
is not straightforward to model the fluxes of heat and salinity
into the mixed layer. In this study, we have modeled this
exchange by considering the local fluxes beneath each ice
category, assuming that the ocean mixed layer is horizontally
homogeneous. In effect, we have considered only the "skin"
drag. As was mentioned above, we have not considered the
"form" drag associated with pressure ridges, nor have we
considered any secondary circulations that might be associated
with the freezing of wide leads. Future modeling efforts will
examine these effects.

In a comparison of several different ice/ocean interfacial
heat flux parameterizations, we have found that differences in the
mixed layer properties and ice mass balance occur depending on the parameterization used. It appears particularly
unreasonable to assume that the mixed layer under sea ice is
unable to store heat during the summer months: this
assumption results in an ice cover which is approximately 10%
thinner than that obtained in the baseline simulation. Double
diffusion and molecular sublayer effects appear to play
important roles in determining the frazil ice production and
basal heat flux values. It is possible to obtain reasonable
present-day simulations by "tuning" relatively simple
parameterizations which ignore these effects. However, these
parameterizations will generally not give reasonable results
under climate change scenarios. The amount of wintertime
frazil ice production and whether this occurs in a localized
region close to the ice/ocean interface or deeper in the water
column remains a question which requires further work and
more observations.

Acknowledgments. This research was funded by NSF OPP-9504261
We would like to thank M. McPhee for providing us with the AIDJEX
ocean data and for comments on the text.

References
Aagaard, K., and E.C. Carmack, The role of sea ice and other fresh
water in the Arctic circulation, J. Geophys. Res., 94, 14,485-14,498,
1989.
Bourke, R.H., and R.P. Garrett, Sea ice thickness distribution in the
Cattle, H., Diverting Soviet rivers: Some possible repercussions for the
Coachman, L.K., and C.A. Barnes, The movement of Atlantic water in
the Arctic Ocean, Arctic, 16, 8-16, 1963.
Colt, G.P.N., and W.P. Weeks, Salinity variations in sea ice, J. Glacial,
Ebert, E.E., and J.A. Curry, An intermediate one dimensional
thermodynamic sea ice model for investigating ice-atmosphere
Ebert, E.E., J.L. Schramm, and J.A. Curry, Disposition of solar radiation
in sea ice and the upper ocean, J. Geophys. Res., 100, 15,965-15,975,
1995.
Fichefet, T., and P. Gaspar, A model study of upper ocean-ice sea
Gaspar, P.D., Modeling the seasonal cycle of the upper ocean, J. Phys.
Harvey, L.D.D., Testing alternative parameterization of lateral melting
and upward basal heat flux in a thermodynamic sea ice model, J.
Hibler, W. D., III, The role of sea ice dynamics in modeling CO2
increases, in Climate Processes and Climate Sensitivity, Geophys.
Ikeda, M., A mixed layer beneath melting sea ice in the marginal ice
zone using a one-dimensional turbulent closure model, J. Geophys.
Kraus, E.B., and J.S. Turner, A one-dimensional model of the seasonal
thermocline, II, The general theory and its consequences, Tellus, 19,
Lemke, P., A coupled one-dimensional sea ice-ocean model, J.
Lemke, P., and T.O. Manley, The seasonal variation of the mixed layer
and the pycnocline under polar sea ice, J. Geophys. Res., 89, 6944-
6004, 1984.
Lemke, P., W.B. Owens, and W.D. Hibler III, A coupled sea ice-mixed
layer- pycnocline model for the Weddell Sea, J. Geophys. Res., 92,
9513-9525, 1990.
Maykut, G.A., Large-scale heat exchange and ice production in the
Maykut, G.A., and M.G. McPhee, Solar heating of the Arctic mixed
Maykut, G.A., and N. Untersteiner, Some results from a time-dependent
thermodynamic model of sea ice, J. Geophys. Res., 76, 1550-1575,
1971.
McPhee, M.G., Tidulet heat and momentum transfer in the oceanic


J. A. Curry, M. M. Holland, and J. L. Schramm, Department of Aerospace Engineering, Program in Atmospheric and Oceanic Sciences, Campus Box 479, University of Colorado, Boulder, CO 80309-0429. (e-mail: curryja@cloud.colorado.edu; hollandsm@orbiter.colorado.edu, schramm@monsoon.colorado.edu)

(Received January 3, 1996; revised January 15, 1997, accepted April 30, 1997.)