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The Sensitivity of a Thermodynamic Sea Ice Model to Changes in Surface Albedo Parameterization

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The sensitivity of a thermodynamic sea ice model to changes in surface energy fluxes in the Arctic is investigated. The main emphasis of the paper is on the testing of the model sensitivity to changes in surface albedo parameterization. Climatologies of turbulent and long-wave fluxes in the Arctic are scarce, and those that exist are shown to generate significant differences in the predicted ice thickness. There is considerable disagreement in the literature on albedo values, and in particular, proposed albedos of bare, puddled ice range from 0.4 to 0.66. The differences among published model simulations are shown to be potentially explicable in terms of this range in bare ice albedo. A new ice albedo parameterization is proposed, and its sensitivity is tested. It is shown that the increase in surface albedo with cloud cover can cause a doubling of the ice thickness, and the need to include melting snow as an albedo class distinct from dry snow is demonstrated. The value of bare-ice albedo is shown to be important in determining whether the ice is in a multiyear or a seasonal ice zone, and the need for more observational data on the extent and role of melt puddles is emphasized.

INTRODUCTION

The extent and thickness of sea ice is an important parameter in the climate system. Presently, considerable effort is being put into simulating the annual behavior of the pack ice with numerical models. For example, *Hibler and Walsh* [1982] use a complex ice dynamical model coupled to a simple thermodynamic model in an attempt to simulate the interannual variations in ice extent. General circulation models (GCM's) now more commonly include ice prediction subroutines; *Washington et al.* [1980] and *Manabe et al.* [1979] report experiments using coupled ocean-atmosphere-ice models. *Manabe and Stouffer* [1980] emphasized the need for realistic cryosphere modeling by finding that the Arctic became ice free in their quadrupled CO_2 experiments. *Pollard et al.* [1983] investigate the coupling of simple mixed-layer ocean models with ice models.

In these models it is necessary either to calculate or specify the surface energy budget fluxes in order to predict the ice thickness, but there are often large differences in these flux specifications. In this paper the sensitivity of a thermodynamic model of sea ice, similar to the ones used in the models noted above, is studied. As will be seen, the prediction of ice thickness is dependent on all components of the surface energy balance, all of which are poorly known for the Arctic. However, the emphasis will be on the sensitivity of the model to surface albedo changes, since the shortwave radiation is the dominant component of the surface energy balance during the summer. It is also a parameter about which there is little agreement. For instance, Figure 1 shows the annual variation of surface albedo at 85°N from three recent surface albedo compilations [*Hummel and Reck*, 1979; *Kukla and Robinson*, 1980; *Robock*, 1980]. It is clear that there are substantial differences in all seasons and that the change between summer and winter albedos varies greatly among the three works. Table 1 shows the ice albedo parameterizations used in several GCM's (not all of which have interactive ice); again, large differences are apparent. Finally, Figure 2 shows three attempts at thermodynamic modeling of the present-day ice in the Arctic; the August simulations of *Hibler and Walsh* [1982] and *Manabe and Stouffer* [1980] are shown, along with the July simulation of *Parkinson and Washington* [1979]. All three models use a snow (or frozen ice) albedo of 0.75 but use very different values for the albedo of bare melting ice (0.66, 0.45, and 0.5, respectively). Though the discrepancies in the surface albedos will not be the sole reason for the differences among the three models, it will be shown that such variations are capable of explaining a substantial degree of the differences in the predicted thicknesses.

The sensitivity of thermodynamic ice models to changes in surface forcing has been investigated previously by *Maykut and Untersteiner* [1971] and *Semtner* [1976]. In these models the specifications of shortwave forcing and surface albedo were based mainly on climatology and were only weakly dependent on surface state. In the present work the albedo is made dependent on surface state, and the shortwave fluxes are calculated by using an interactive scheme. Further, the earlier models placed much emphasis on attaining a reasonable equilibrium ice thickness and rejected certain albedo specifications or flux climatologies because of the prediction of inappropriate ice thicknesses. This paper shows that the degree of uncertainty in almost all aspects of the energy balance of the ice is so great that it is possible to achieve reasonable ice thicknesses by holding fixed one set of fluxes or parameters and by seemingly legitimate tuning of others.

After a brief description of the model used in this study the model sensitivity to changes in turbulent and long-wave flux climatologies is examined, and then a detailed examination of the model sensitivity to changes in the surface albedo specification is made.

BRIEF DESCRIPTION OF THE THERMODYNAMIC ICE MODEL

The three-layer model presented by *Semtner* [1976] is used here. Recently, *Semtner* [1984] has shown that the use of single-layer ice models (as used, for example, by *Parkinson and Washington* [1979] and *Hibler and Walsh* [1982]) can lead to serious deficiencies in the seasonal cycle of ice thickness and

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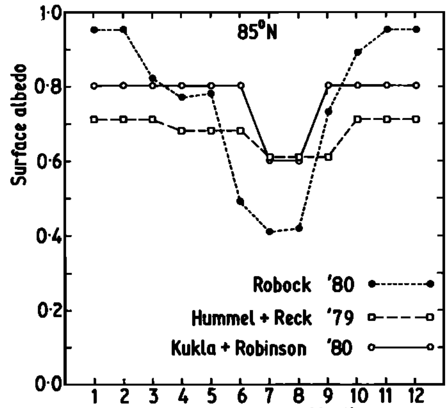

Fig. 1. The variation of surface albedo with month at 85°N from the surface albedo compilations of *Hummel and Reck* [1979], *Kukla and Robinson* [1980], and *Robock* [1980].

concluded that a three-layer model has the minimum resolution permissible for detailed ice modeling work.

The model resolves two internal ice temperatures and one internal snow temperature and was shown by *Semtner* [1976] to perform well when compared with the more complex model of *Maykut and Untersteiner* [1971]. Figure 3 shows the main concepts of the model. The thermodynamic forcing is specified either from climatology or by calculation. In the present study the latent and sensible heat fluxes, the downward long-wave flux from the atmosphere, and the flux of heat from the ocean to the underside of the ice are specified, although the sensitivity of the model to changes in these parameters is investigated in the next section. The climatologies are taken from Semtner's Table 1, and the same snowfall rates are specified; twelve 30-day months are assumed, with 8-hour time steps and with values of the fluxes evaluated from cubic polynomial interpolation from the mid-month value. In the initial experiments, described in the next section, the shortwave forcing and albedo parameterization based on climatology, as used by *Semtner* [1976], are employed. In this albedo representation the bare-ice albedo is 0.64. The correct value of the Stefan-Boltzmann constant is adopted here (see *Semtner* [1976, p. 383]; it should also be noted that the value given by *Semtner* [1976] is actually in cal cm^{-2} K^{-4} s^{-1} and not in erg cm^{-2} K^{-4} s^{-1} as was printed). The present model results are therefore not directly comparable with those of *Semtner* [1976].

In all the experiments presented here, two values for the oceanic heat flux F_B are used; the "conventional" values used in these models is 2.0 W m^{-2}, but evidence for a flux of this magnitude is lacking [see, for example, *McPhee and Untersteiner*, 1982]. Consequently, calculations were also performed using a value for F_B of 0.0 W m^{-2}.

The model was run for 65 years, unless an equilibrium thickness was achieved beforehand.

SENSITIVITY TO CHANGES IN FORCING

Long-Wave Radiation From the Atmosphere

The long-wave data set used by *Semtner* [1976] is based on Soviet calculations from *Marshunova* [1966] and averaged by *Fletcher* [1965]; Table 2 shows the mean annual thicknesses attained for the two values of the oceanic heat flux used here. If the central Arctic values given by *Vowinckel and Orvig* [1970] are substituted, then, as Table 2 shows, the model-predicted thickness can change by almost a factor of 2. Inspection of the two curves for the long-wave flux (Figure 4) shows what might be considered to be rather small differences. In fact the crucial difference is in the springtime long-wave flux; this difference is indicative of the uncertainties in the long-wave flux as a result of the paucity of observational data. Replacing Vowinckel and Orvig's June value by Fletcher's value accounts for practically all the difference between the two ice thicknesses; this is because of the crucial role that the length of the bare-ice melt season has on the predicted thickness. A higher long-wave flux leads to a more rapid snow melt and a longer ice ablation season.

Surface Turbulent Heat Fluxes

Reported values for the turbulent heat fluxes vary widely [e.g., *Maykut*, 1983]; Figure 5 shows the annual variation of sensible and latent heat fluxes from *Doronin* [1963] and *Leavitt et al.* [1978]. There are substantial differences; the Doronin data given an annual net loss of heat from the surface, while the Leavitt et al. data give a net gain of heat. Both sets are based on calculations and are not from direct observations; Doronin's results are based on the largest amount of data, while Leavitt et al. employ a more sophisticated method for calculation. At present there are insufficient observational data from which to choose between the above estimates [*Maykut*, 1983], and until such data become available, Figure 5 indicates the uncertainty in the turbulent heat flux specification. Table 2 shows the influence of the different data sets on the predicted thickness; again the differences are of the order of a factor of 2. (For some results a range of ice thicknesses is given. In these cases the ice is undergoing interannual variations: these occur when open water appears in the course of an integration, as explained by *Semtner* [1976].)

The main point to come from these sensitivity studies is that

TABLE 1. Parameterization of Ice Surface Albedo in Various General Circulation Models

Model	Reference	Albedo (T, surface temperature; ϕ, latitude)
GLAS	*Herman and Johnson* [1980]	always 0.7.
GFDL(*a*)	*Wetherald and Manabe* [1981]	0.7 $T \leq 263$ K 0.35 $T > 263$ K
GFDL(*b*)	*Manabe and Stouffer* [1980]	0.5 $\phi < 55°$ 0.7 $\phi > 66.5°$ 0.45 if top surface melting
UKMO	*Corby et al.* [1977]	0.8 $T < 271.2$ K 0.5 $T \geq 271.2$ K
GISS	*Hansen et al.* [1983]	0.45 bare higher if snow covered

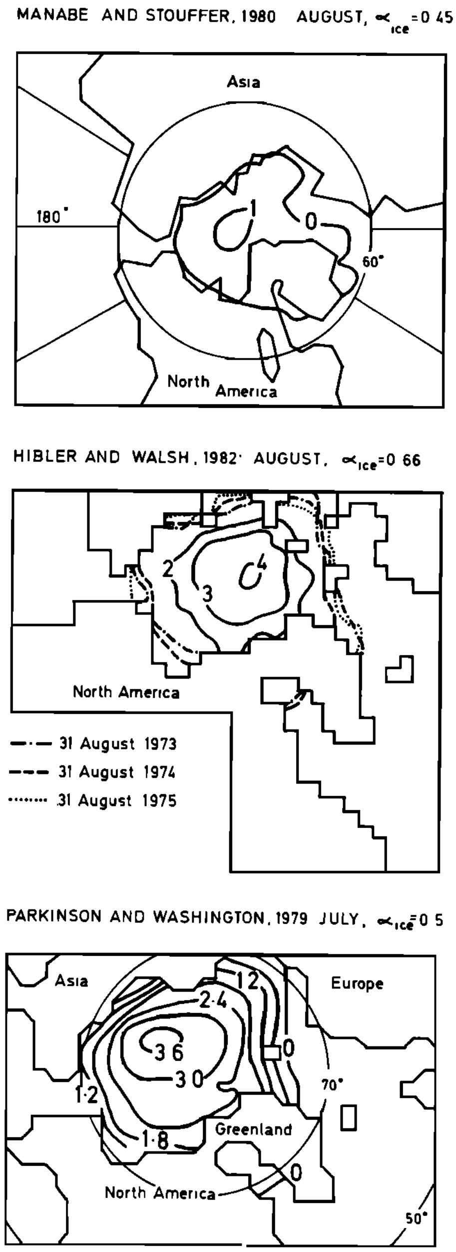

Fig. 2. Predictions of summer ice thickness in the Arctic, using thermodynamic ice models from *Hibler and Walsh* [1980] (August simulation); *Parkinson and Washington* [1979] (July); and *Manabe and Stouffer* [1980] (August). The bare-ice albedos used in these simulations are 0.66, 0.5, and 0.45, respectively.

the accurate prediction of ice thickness in a model is evidently going to be difficult when variations among the available climatologies generate such large differences. Further, there is a temptation to tune the ice parameters to give a reasonable equilibrium ice thickness: one easily tuned parameter is the surface albedo, [e.g., *Pollard et al.*, 1983], but the legitimacy of such tuning is highly questionable in view of the sensitivity of ice thickness to other parameters.

SOLAR RADIATION AND ALBEDO PARAMETERIZATIONS

The original *Maykut and Untersteiner* [1971] and *Semtner* [1976] models provide only weak coupling between the absorbed shortwave radiation, the surface albedo, and the model state. In GCM's it is more likely that shortwave fluxes will be calculated with radiative transfer schemes of reasonable complexities and that the albedo will be made dependent on the surface state. In this section, factors important in the specification of the shortwave flux are investigated. Potentially important factors in modeling the shortwave flux include the dependence of shortwave radiation on cloud optical thickness, the modeling of multiple reflections between ground and cloud base, and the dependence of snow and ice surface albedos on cloudiness. By using different parameterizations for the flux in the clear and cloudy portions of the sky, different surface albedos can be employed. Actual month lengths are now used with the time step unchanged at 8 hours, and cubic interpolation from the mid-month values of the climatological specifications is performed. The shortwave radiation calculations are performed for 80°N, with the other flux specifications typical of a multiyear ice zone (as given by *Semtner* [1976]).

The shortwave radiation is calculated by using parameterizations based on the 24 spectral band delta-Eddington model of *Slingo and Schrecker* [1982; see *Shine*, 1984]. For cloudy skies the net flux at the surface (in W m^{-2}) is given by

$$F_N = (53.5 + 1274.5\mu)\mu^{0.5}(1 - 0.996\alpha) \div (1 + 0.139(1 - 0.9345\alpha)\tau) \quad (1)$$

where τ is the cloud optical thickness, α the surface albedo, and μ the cosine of the solar zenith angle.

The cloud optical thickness used in (1) is given by the expression

$$\tau = (3/2)(LWP/r_e) \quad (2)$$

where LWP is the liquid water path in grams per square meter and r_e the equivalent droplet radius in microns. This expression provides a good approximation to the optical depth at visible wavelengths [e.g., *Slingo and Schrecker*, 1982]. It should be noted that although τ from (2) is used as an input parameter to (1), (1) was derived by using a wavelength-dependent optical thickness.

For clear skies the expression of *Zillman* [1972] is adapted to provide better agreement with the detailed scheme so that

$$F_N = (1368.0\mu(1 - \alpha))/(1.2\mu + (1.0 + \mu)e_a\ 10^{-3} + 0.046) \quad (3)$$

where e_a is the surface water vapor pressure (mbar). This is calculated on the assumption that the near-surface air has a relative humidity of 90%.

These expressions agree with the *Slingo and Schrecker* [1982] results to within a few percent. The functional forms correctly reproduce the dependence of the surface flux on solar zenith angle and surface albedo. Its use is an improvement on albedo change experiments reported by *Maykut and Untersteiner* [1971] and *Semtner* [1976]. In these models the surface shortwave flux incident on the surface was specified by climatology and multiplied by (1 − surface albedo) to obtain the net flux. This procedure will exaggerate the change of net flux on changing the surface albedo, since multiple reflections between cloud base and surface act to reduce the dependence of the net flux at the surface on the surface albedo.

It is emphasized that the simulations presented in this section are not to be taken as predictions of ice thickness; the attainment of a reasonable equilibrium ice thickness (of about 3 m in the central Arctic) with any particular albedo parameterization does not indicate that that albedo parameterization is correct. The results presented in the previous section make

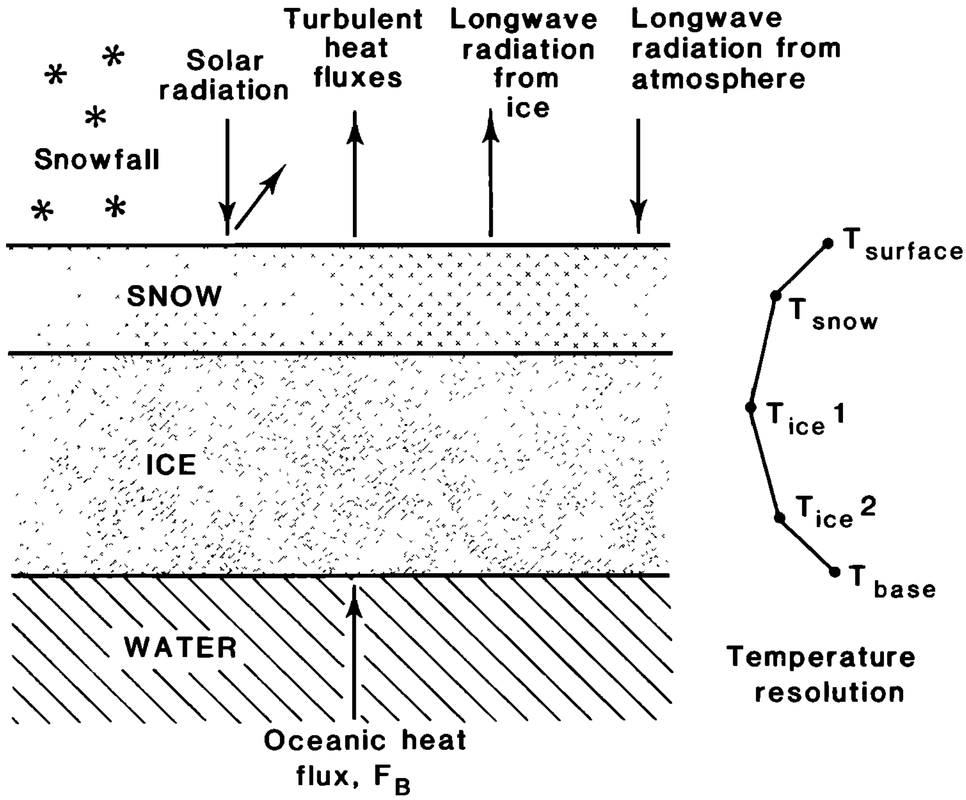

Fig. 3. Main components of the thermodynamic ice model.

it clear that, using any particular albedo set, realistic ice thicknesses could be attained by altering the downward long-wave fluxes or the turbulent heat fluxes. The purpose of the calculations presented here is to emphasize the important physical parameters that determine the shortwave radiation absorbed by the ice and the uncertainties created by a lack of adequate knowledge of the value of particular parameters.

The first experiment uses a very simple albedo parameterization similar to the one used in the thermodynamic simulations shown in Figure 2. Here the snow albedo is taken as being 0.75, and the bare ice albedo is varied from 0.75 to 0.4. The results are shown in Table 3. The impact of changing the bare-ice albedo from 0.65 to 0.45 is substantial and is clearly capable of explaining the differences among the models shown in Figure 2. The bare-ice albedo crucially affects whether ice will entirely melt during the summer—a particularly important problem for simulating the ice edge position in summer. (Generally, mean annual ice thicknesses less than about 1 m indicate that the ice has disappeared in summer.)

TABLE 2. Dependence of Predicted Mean Annual Ice Thickness (m) on the Particular Long-Wave and Turbulent Heat Flux Climatologies Used

Description		Oceanic Heat Flux, W m^{-2}	
Longwave	Turbulent	0.0	2.0
Fletcher [1965]	*Doronin* [1963]	2.30	1.25
Vowinckel and Orvig [1970]	*Doronin* [1963]	4.39	2.25
Fletcher [1965]	*Leavitt et al.* [1978]	1.20–1.14	0.82
Vowinckel and Orvig [1970]	*Leavitt et al.* [1978]	1.5	0.83–0.89

Results shown use oceanic heat fluxes of 0.0 and 2.0 W m^{-2}.

In order to investigate the important components in albedo parameterizations, a relatively complex parameterization was constructed that takes into account the important physical influences on the ice surface albedo. The parameterization is summarized, along with references, in Table 4. The important surface types are dry snow; melting snow; thin melting snow on ice; bare, puddled ice; thin melting ice; freezing ice; and

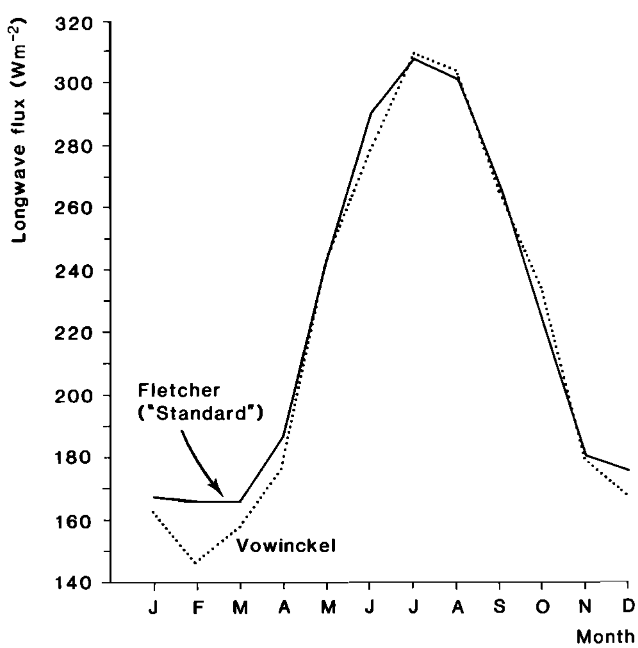

Fig. 4. The variation of downward long-wave radiation from the atmosphere (W m^{-2}) with month for the central Arctic climatologies of *Fletcher* [1965] and *Vowinckel and Orvig* [1970].

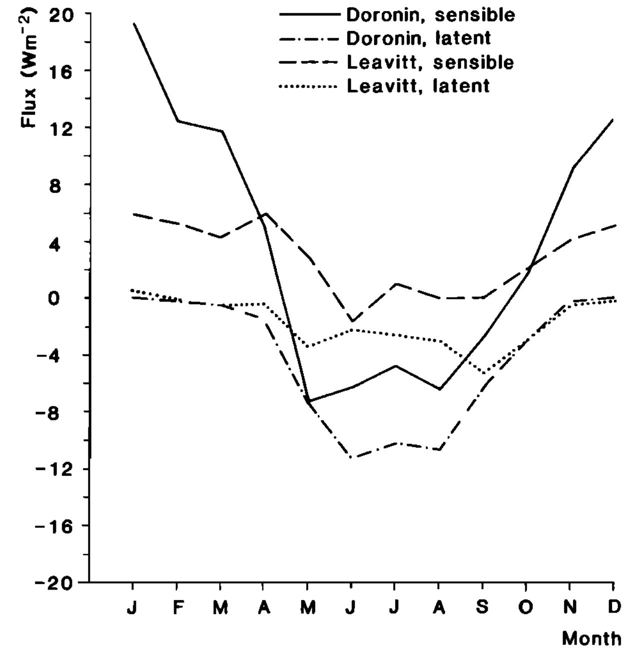

Fig. 5. The variation of latent and sensible heat fluxes at the surface (W m^{-2}) with month for the Arctic from *Doronin* [1963] and *Leavitt et al.* [1978].

thin snow on freezing ice. If open water appears in the course of an integration, it is assigned an albedo of 0.1.

Since snow and ice albedos are high in the visible and low in the infrared, the effect of cloud is to cause an increase in the spectrally averaged albedo as a result of the depletion of the solar radiation in the near-infrared below the cloud. The albedos in Table 4 are intentionally clear-sky ones. From theoretical calculations and measurements [e.g., *Grenfell and Maykut*, 1977; *Grenfell*, 1979] the cloudy-sky albedos were taken as being 0.07 higher than the clear-sky albedos for all albedos greater than 0.28. (For lower albedos, generally thin melting ice or water, the albedo is relatively independent of wavelength.)

For all the experiments reported here a cloud optical thickness of 7.5 is used; it represents a reasonable average from Arctic cloud measurements [*Shine et al.*, 1984]. However, ice thicknesses are significantly dependent on the cloud optical thickness used (in the absence of any compensating feedback from the long-wave fluxes from the atmosphere). Using the *Vowinckel and Orvig* [1970] long-wave data set and an oceanic heat flux of 0.0 W m^{-2}, changing the optical thickness from 5 to 10 increases the ice thickness from 1.63 to 4.47 m; such cloud thickness variations are easily within the range used in different climate models. The cloud amount data for 80°N are taken from *Vowinckel* [1962].

TABLE 3. Impact of Changing Ice Albedo on the Mean Annual Ice Thickness (m) for Cloud of Optical Thickness 7.5 and a Snow Albedo of 0.75

	Oceanic Heat Flux, W m^{-2}	
α_{ice}	0.0	2.0
0.75	12.32+	6.61+
0.65	3.64	1.89
0.60	2.07	1.04
0.50	0.86–0.89	0.73
0.45	0.81	0.68–0.99
0.40	0.72–1.01	0.70–1.00

The bare-ice albedo is varied from 0.75 to 0.4. Results are for the Fletcher long-wave flux and the Doronin turbulent fluxes. A '+' sign indicates that an equilibrium thickness had not been attained in 65 simulated years.

Table 5 presents the modeled equilibrium ice thicknesses and their dependence on factors determining the absorbed shortwave radiation. Using the albedo parameterization as shown in Table 4, the predicted ice thickness is between 1.88 and 3.61 m for the downward long-wave and turbulent heat flux parameterizations used here.

In the first experiment the increase in surface albedo between clear and overcast skies was neglected. The overall lowering of the albedo resulted in the predicted equilibrium thickness being decreased by 50% (Table 5). The response is large because small fractional changes in high albedos lead to large fractional changes in the shortwave radiation absorbed by the surface. Any climatic change experiment resulting in changed cloudiness at high latitudes may be expected to produce different results if the modification in surface albedo as a result of cloudiness has been neglected.

The neglect of multiple reflections between the cloud base and the surface leads to a serious underestimate of the shortwave flux. In Table 5 it can be seen that for the model specifications used here, unphysical snow/ice conditions occur. The shortwave radiation is unable to melt the snow during summer, and an unrealistic accumulation of snow occurs. As will be seen, such unrealistic snow accumulations can occur in other conditions and have also been noted by *Pollard et al.* [1983].

The effect of changes to the surface albedo parameterization on the ice thickness are now considered (results are shown in Table 5). In all these experiments the clear-sky/cloudy-sky surface albedo difference is retained. Figure 1 indicated some differences in the wintertime (i.e., snow-covered) ice albedo among various albedo compilations. The dry-snow albedo was decreased from 0.8 to 0.75. The equilibrium ice thicknesses decreased by over a meter. It was found that the date of snow melt and the date of appearance of bare ice were about 1 week earlier with the decreased albedo; this led to a longer ice ablation season and thinner ice. However, it is considered that a clear-sky deep-snow value of about 0.8 is more appropriate from considerations of the work of, for example, *Marshunova* [1966], *Grenfell and Maykut* [1977], and *Bryazgin and Koptev* [1969].

The change of snow albedo, with the onset of melting, suggested in the observations of *Langleben* [1966] and *Strokina* [1980] clearly plays an important role. Indeed, the neglect of melting snow as a class distinct from dry snow results in a continuous snow accumulation, since the snow fails to entirely melt during the summer, and the unphysical snow/ice conditions occur. The actual value for a melting snow albedo is less certain; a change from 0.65 to 0.7 can be seen to lead to a thickening of the ice of 1 m. As might be anticipated, a higher melting-snow albedo leads to a slower snow melt and a shorter ice albation season. Bare ice was found to appear 4 days later when using the higher albedo.

In Table 4 a 'thin melting snow class' was included to represent the period in which snow cover becomes patchy and bare ice begins to appear. Little data exist to indicate a mean snow depth at which this patchiness occurs, but from *Bryazgin and Koptev* [1969] it was estimated to occur at about 10 cm. However, Table 5 shows that the inclusion of this snow classification is relatively unimportant and causes only a slight

TABLE 4. Snow/Ice Albedo Parameterization

Albedo Class		Value	References, examples
Dry snow	α_d	0.8	[*Marshunova*, 1966; *Grenfell and Maykut*, 1977]
Melting snow	α_m	0.65	[*Bryazgin and Koptev*, 1969; *Langleben*, 1966; *Strokina*, 1980]
Thin melting snow on bare ice	α_{mb}	$= \alpha_b + ((\alpha_m - \alpha_b)/0.1)h_s \quad h_s < 0.1$ m	[*Bryazgin and Koptev*, 1969]
Bare puddled ice	α_b	0.53	[*Langleben*, 1971; *Grenfell and Maykut*, 1977]
Thin melting ice	α_{btm}	$= 0.472 + 2.0(\alpha_b - 0.472)(h_i - 1.0) \quad 1.0 \le h_i \le 1.5$ $= 0.2467 + 0.7049\, h_i - 0.8608\, h_i^2 + 0.3812\, h_i^3 \quad 0.05 \le h_i \le 1.0$ $= 0.1 + 3.6\, h_i \quad 0.0 \le h_i \le 0.05$	[*Miller*, 1979; *Weller*, 1972]
Thin forming ice	α_{btf}	As α_{btm} for $0.0 \le h_i \le 1.0$ $= 0.472 + 2.0(\alpha_{bf} - 0.472)(h_i - 1.0) \quad 1.0 \le h_i \le 1.5$	
Bare frozen ice	α_{bf}	0.72	[*Grenfell and Maykut*, 1977]
Snow on frozen ice	α_{df}	As α_d for $h_s \ge 0.05$ $= \alpha_{btf} + h_s(0.8 - \alpha_{btf})/0.05 \quad h_s \le 0.05;\ h_i \le 1.5$ $= \alpha_{bf} + h_s(0.8 - \alpha_{bf})/0.05 \quad h_s \le 0.05;\ h_i \ge 1.5$	[*Grenfell*, 1979]

The variable h_s is the snow depth in meters; h_i is the ice depth in meters. The tabulated values are for clear skies. Albedos for cloudy skies are 0.07 higher for all albedos greater than 0.28.

(10–20 cm) increase in the mean ice thickness. The snow ablation period is little affected because the snow is melting so rapidly at this stage in any case.

It is clear from the introduction (especially Figures 1 and 2) that the most difficult albedo parameter to define is that of melting bare ice. Melting bare ice is partially covered by melt puddles, which act to reduce substantially the surface albedo [e.g., *Langleben*, 1971; *Grenfell and Maykut*, 1977]. However, there are few data on climatological melt pond coverage—the albedo value of 0.53 assumes a puddling of 15%. The situation is further complicated by the fact that it is not clear what role melt puddles play in ice ablation. Although they have a substantially lower albedo than bare ice, they often refreeze completely in late summer and have little net effect on the ice thickness [see, for example, *Maykut*, 1983]. *Hanson* [1965], however, shows that albation does appear to increase in ponded areas. In regions of seasonal ice the puddles must have a substantial net impact, since melt holes can form through the ice, which leads to surface drainage [e.g., *Weaver et al.*, 1976]. Further, as discussed by *Andreas and Ackley* [1982], the conditions for melt puddle formation are unfavorable in the Antarctic. Two experiments changing the bare, puddled ice albedo were performed: one assumes no puddling, the other, a puddling of 25%, which gives bare ice albedos of 0.58 and 0.50, respectively. There is almost a factor of 2 difference between the ice thicknesses in the two cases. The choice of bare-ice albedo is clearly important, and other experiments (and reference to Table 3) have indicated that for thinner initial ice conditions a change in albedo from 0.5 to 0.58 would influence whether ice belonged to a seasonal or multiyear ice zone. More observational data are evidently required.

TABLE 5. Mean Annual Equilibrium Ice Thickness (m) for the Albedo Parameterization Shown in Table 4 and Changes Resulting From Alterations in the Shortwave Flux or Albedo Specifications

	Oceanic Heat Flux, W m^{-2}	
Description	0.0	2.0
Basic	3.61	1.88
No increase in cloudy sky surface albedo	1.55	0.77–1.02
Neglect multiple reflections	unlimited snow accumulation	unlimited snow accumulation
Dry snow albedo = 0.75	2.48	0.81–0.84
No melting snow class	unlimited snow accumulation	unlimited snow accumulation
Melting snow albedo = 0.7	4.56	2.26
No thin melting snow on ice class	3.70	2.01
Bare ice albedo = 0.58 (no puddling)	5.60+	2.76
Bare ice albedo = 0.50 (25% puddling)	2.89	1.53
Ice albedo dependent on thickness at 2.0 m	3.61	1.65

Maykut and Untersteiner [1971] found that changing their bare ice albedo from 0.64 to 0.54 lead to a change in ice thickness of 1.83 m. For the more sophisticated shortwave flux parameterization used here the change of ice thickness with ice albedo is smaller; the change of 0.08 shown in Table 5 leads to a change of 1.23 m. It is also important to note that reasonable ice thicknesses can be obtained by using the more realistic values of bare ice albedo used here. Maykut and Untersteiner had called into doubt the use of low, bare-ice albedos because the predicted ice thickness was too small.

The 'thin melting ice' albedo class will show a similar sensitivity to changes as the bare-ice albedo; little observational data exist for this class, mainly because it is a physically dangerous measurement to perform [see, for example, *Langleben*, 1966]. The parameterization used here is from *Miller* [1979], who produced curve fits to data from *Weller* [1972]. In the present work there is a presumed linear dependence of albedo on ice thickness between Miller's 1-m value and the thick bare, puddled ice albedo at 1.5 m. An experiment was performed for which the linear dependence was instead between 1.0 and 2.0 m. In this case, only the integrations using the oceanic heat flux of 2.0 W m^{-2} in Table 5 will be affected, since only here does the summer ice thickness fall below 2.0 m. Table 5 shows that the ice thins by over 20 cm. The precise form of the dependence of albedo on the ice thickness is likely to be important in zones of thin ice; the positive feedback between ice thickness and albedo will lead to an acceleration of the ice melt. The treatment of thin ice is complicated by the fact that a fraction of the unreflected radiation passes through the ice to the underlying water and so does not take part directly in the melting of the ice [e.g., *Grenfell*, 1979; *Maykut*, 1982]. This effect is not accounted for here. However, since this subice water must be close to the freezing point, any absorption of the radiation transmitted through the ice by the water must lead to a heating of the subice water and a subsequent melting of the ice. *Maykut* [1982] assumes that 35% of the transmitted radiation is immediately returned to the ice by the oceanic heat flux. In the absence of a more complex model of the subice water it seems energetically more consistent to allow all the unreflected radiation to contribute directly to melting the ice.

A CAVEAT

The sensitivities listed in Table 5 are based on the assumption that the turbulent heat fluxes and downward long-wave fluxes from the atmosphere are independent of model state. In fact a melting snow or ice surface is likely to have an increased turbulent heat flux, which may delay the speed of snow or ice melt, and changed atmospheric temperatures will have an impact on the downward long-wave flux. Hence the model as presented neglects certain feedbacks and so may not properly represent the dependence of ice thickness on changes in the albedo parameterization. Nevertheless the results presented in Table 5 clearly indicate the first-order effects that inadequate modeling of either the solar radiation field or the surface albedos can generate.

CONCLUSIONS

A thermodynamic model of sea ice has been used to show that the present uncertainty in the radiative and turbulent heat fluxes will seriously limit the predictability of sea ice thickness. In particular it is shown that the use of surface albedo as a tunable parameter in these models should only be undertaken with caution because other factors, such as the different downward long-wave flux or the turbulent heat flux climatologies, can generate a factor of 2 uncertainty in ice thickness.

A relatively complete shortwave flux parameterization is used and coupled to a surface albedo parameterization of a higher complexity than those used in present numerical models. These are the main points to come from these experiments:

1. Solar radiation codes in models must include the effect of cloud-to-ground multiple reflections, otherwise the surface net flux will be significantly underestimated, with serious effects on ice thickness and extent.

2. The surface albedo change between clear and cloudy skies, as a result of the depletion of the near-infrared component of the solar beam by clouds, has a large (factor of 2, in this case) impact on ice thickness.

3. The inclusion of a 'thin snow on ice' albedo class has a relatively small impact on ice thickness, but the representation of melting snow as a distinct class from dry snow is clearly important.

4. The most serious problem appears to be the specification of an albedo for bare, melting ice. Observational data indicate albedos between 0.5 and 0.58. The ice thickness can be affected by a factor of 2 between these albedo values and can affect whether ice is multiyear or seasonal. More observational data are required to assert the role of puddled areas on the overall ablation rate and also to obtain more widespread data on the areal extent of puddling.

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