JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. C2, PAGES 3839–3849, FEBRUARY 15, 1996

Evaluation of surface radiative flux parameterizations for use in sea ice models

Jeffrey R. Key
Department of Geography, Boston University, Boston, Massachusetts

Robert A. Silcox and Robert S. Stone
Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder

Abstract. The surface radiation budget of the polar regions strongly influences ice growth and melt. Thermodynamic sea ice models therefore require accurate, yet computationally efficient methods of computing radiative fluxes. In this study a variety of simple parameterizations of downwelling shortwave and longwave radiation fluxes at the Arctic surface are examined. Parameterized fluxes are compared to in situ measurements over an annual cycle. Results suggest that existing parameterizations can estimate the downwelling shortwave flux to within 2% in the mean, with a root-mean-square error (RMSE) of about 4% for clear skies and 21% for cloudy conditions. Parameterized longwave fluxes are accurate to within 1% in the mean, with RMSE values of 6% for both clear and cloudy skies. On the basis of these results, two parameterization schemes are recommended to estimate radiation forcings in sea ice models for Arctic applications.

Introduction

The sea ice cover is controlled by dynamic processes (wind, ocean currents) and thermodynamic processes (heat from the ocean and leads, sensible heat from the atmosphere, latent heat from the phase change of water, and downwelling shortwave and longwave radiation). Over thick ice in the Arctic, the downwelling radiation flux is typically 2 orders of magnitude greater than either the turbulent or oceanic flux. One would therefore expect sea ice models to be sensitive to the radiative fluxes used to drive them. For example, in the two-dimensional dynamic-thermodynamic ice model described by *Maslanik et al.* [1995], a 10% change in the longwave flux changes the computed mean ice mass by 36%. A 10% increase in the shortwave flux decreases the mean ice mass by 11%, while a 10% decrease in the shortwave flux increases ice mass by 8%. Accurate simulations of sea ice therefore require accurate forcings of the downwelling radiation fluxes.

Because the downwelling surface radiation fluxes are a complex function of many variables in the entire atmospheric column, the most accurate computation of fluxes is likely to be through the use of a radiative transfer model. However, the application of such schemes is only possible if all the required model input data (e.g., vertical distributions of temperature and moisture, cloud properties, and aerosols) are available. In the absence of such a complete description of the surface and atmosphere, thermodynamic sea ice models have incorporated simple radiative flux parameterizations which require only a few input variables. It is important to know which schemes are most accurate, what the main problems or errors associated with them are, and if they can be improved.

The objective of this study is to evaluate the accuracy of a variety of parameterizations for downwelling shortwave (SW↓) and longwave (LW↓) radiative fluxes that can be used in dynamic-thermodynamic sea ice models. The shortwave parameterizations used are those of *Moritz* [1978], *Bennett* [1982] and *Shine* [1984] for clear skies and those of *Berliand* [1960], *Jacobs* [1978], *Bennett* [1982] and *Shine* [1984] for cloudy skies. The longwave parameterizations computed are those of *Efimova* [1961], *Marshunova* [1966], *Idso and Jackson* [1969], *Zillman* [1972], *Maykut and Church* [1973], *Ohmura* [1981] and *Andreas and Ackley* [1982] for clear skies and those of *Marshunova* [1966], *Maykut and Church* [1973], *Zillman* [1972] and *Jacobs* [1978] for cloudy skies.

To assess the accuracy of the various parameterization schemes we take the following approach: (1) Parameterized SW↓ and LW↓ fluxes are computed using input data from ground-based observations of atmospheric variables over several weeks during the spring of 1993 at Resolute, Northwest Territories, Canada, and over an annual cycle at Barrow, Alaska (Figure 1). Computed fluxes are then compared with the observed downwelling longwave and shortwave fluxes at these sites. (2) Parameterized SW↓ and LW↓ fluxes based on input data from the International Satellite Cloud Climatology Project (ISCCP) monthly (C2) data set are compared with the Arctic flux climatologies of *Vowinckel and Orvig* [1962], *Marshunova* [1966] and *Schweiger and Key* [1994] for nine Arctic locations (Figure 1).

Surface Radiation Fluxes: Sensitivities

Shortwave radiation enters the Earth's atmosphere where it is absorbed, scattered, and transmitted. Some of the energy is absorbed by the ground and reemitted in the form of longwave (thermal) radiation which is also absorbed, scattered, or transmitted, a portion of which is reradiated by the atmosphere. In particular, ozone, oxygen, carbon dioxide, water vapor, aerosols and clouds in the troposphere absorb and scatter radiation. Clouds reflect some of the incident shortwave radiation back to space but also cause multiple reflections between the surface and the cloud base, which contributes a substantial amount to the downward flux over high albedo surfaces. The downwelling longwave flux is the result of emission and scattering in the entire atmospheric column, although the lowest layers, especially the bottom 100 m, are most

Paper number 95JC03600.
0148-0227/96/95JC-03600$05.00

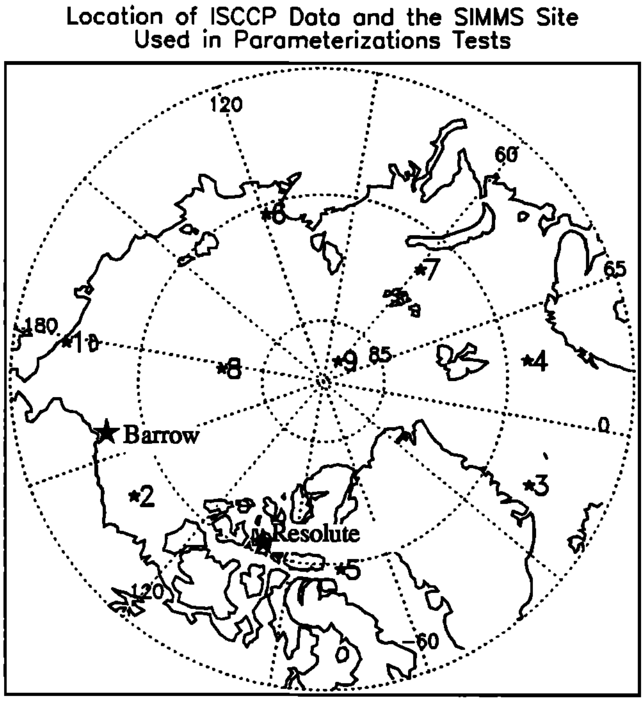

Figure 1. Locations of the in situ measurement sites (Resolute and Barrow) and the International Satellite Cloud Climatology Project cells used in flux comparisons.

important [*Konzelmann et al.*, 1994]. It is typically parameterized as a function of the near-surface temperature and the atmospheric emissivity. The effects of clouds are implicit in this relationship. Water vapor and carbon dioxide are especially good absorbers and emitters of longwave radiation, thus their concentration in the lower troposphere strongly affects the downwelling flux at the surface. The temperature profile in the lower troposphere and the effects of clouds (cloud fraction, base height, temperature, thickness, and microphysical characteristics), including ice crystal precipitation, are very important.

Which atmospheric and surface parameters exert the greatest influence on surface radiative fluxes? In an attempt to answer this question, tests were performed to investigate the sensitivity of the shortwave and longwave downwelling surface radiative flux to prescribed changes in a number of variables. A two-stream radiative transfer model [see *Key*, 1994, and references therein] was used to compute fluxes under a variety of atmospheric and surface conditions. A reference atmosphere was prescribed for both clear and cloudy conditions, and variables were varied over a range of values most likely to occur in the Arctic. Standard sub-Arctic temperature and humidity profiles were used for the summer, the solar zenith angle was 65°, the total precipitable water amount was 1.5 cm, the total aerosol optical depth was 0.1, the atmospheric ozone amount was 375 Dobson units, and the surface albedo was 0.5. For cloudy conditions, low-level stratus water clouds were prescribed with the cloud base height set to 400 m, the cloud thickness was 400 m, the cloud droplet effective radius was 7 μm, and the cloud liquid water content was 0.2 g m^{-3} based on observations of Arctic stratus in the summer by *Tsay and Jayaweera* [1984]. Under these prescribed conditions the shortwave flux was 435 W m^{-2} under clear skies, and 188 W m^{-2} under cloudy skies, and the longwave flux was 288 W m^{-2} under clear skies, and 372 W m^{-2} under cloudy skies.

Table 1 shows the sensitivity of SW↓ and LW↓ to variations in the prescribed values for the reference case. For the variables listed in Table 1 the reference value (above) was changed to each of the two extreme values in the "Range of Change" column and the fluxes were recalculated. The differences between the fluxes for the two extreme values and the ratios of these differences to the reference case fluxes are given in the last two columns. It was found that both SW↓ and LW↓ are sensitive to the concentration of aerosols in the troposphere but with opposite effects, which is also true of precipitable water and ozone amounts and, to some extent, cloud thickness. The negative shortwave and positive longwave responses to changes in these variables results from opposing atmospheric or cloud "albedo" and "greenhouse" effects, respectively. The albedo effect is greatly enhanced when the visible optical depth of clouds increases either as a result of diminishing mean drop size or increases in geometric thickness or water content. Because Arctic stratus tends to be "black" (near unit emissivity) at long wavelengths [cf. *Stephens and Webster*, 1981], the greenhouse effect is much less sensitive to changes in cloud thickness, drop size spectra, or cloud water content but is more sensitive to cloud base height because this affects the effective emission temperature of the cloud through the Stefan-Boltzmann law. The greenhouse effect is more pronounced, however, when skies are clear if precipitable water or aerosol content increases because the effective emissivity of the intervening atmosphere is

Table 1. Sensitivity of the Downwelling Shortwave *SW*↓ and Longwave *LW*↓ Radiative Flux to Variations in Arctic Atmosphere Variables

Variable	Range of Change	Sky Condition	Change in *SW*↓ (W m^{-2})	Change in *LW*↓ (W m^{-2})
Precipitable water, cm	1.0 - 1.8	clear	7 (2)	16 (6)
Ozone amount, DU	300 - 450	clear	2 (0)	1 (0)
Aerosol optical depth, unitless	0.06 - 0.2	clear	26 (6)	12 (4)
Surface albedo, unitless	0.4 - 0.8	clear	22 (5)	0 (0)
		cloudy	116 (62)	0 (0)
Cloud base height, km	0 - 1.6	cloudy	1 (0)	16 (4)
Cloud thickness, m	100 - 700	cloudy	169 (90)	4 (1)
Cloud drop size radius, μm	4.0 - 10.0	cloudy	83 (44)	1 (0)
Cloud liquid water content, g m^{-3}	0.1 - 0.3	cloudy	101 (54)	1 (0)

Numbers in parentheses indicate the percent of change. DU is Dobson units.

much more susceptible to change. Clearly, for the simulations evaluated here the shortwave albedo effect dominates the surface radiation balance during the Arctic summer, with shortwave cloud radiative forcing being most sensitive to changes in physical and/or microphysical properties. Under clear summer skies, competing shortwave and longwave effects tend to cancel when surface conditions remain stable; thus the net radiation balance is rather insensitive to changes in atmospheric structure.

Because, overall, SW↓ is most sensitive to changes in surface and atmospheric conditions, one might expect that simple parameterizations of this quantity are most prone to uncertainties and that this would be especially true when clouds are present in the atmosphere. In subsequent sections it will be shown, through comparisons with in situ observations, that fluxes estimated using various parameterization schemes are least accurate for shortwave calculations under cloudy conditions. Improvements to parameterizations of shortwave fluxes under cloud cover will require significant refinements most likely involving the addition of parameters that accurately characterize cloud physical and microphysical properties.

Parameterization Schemes

Radiation parameterizations are simple schemes or equations which require just a few input variables to estimate radiative fluxes. They do not treat explicitly many important physical processes in the atmosphere but, instead, employ empirical relationships to predict radiative fluxes. Here radiative flux equations are categorized into clear sky and all-sky fluxes for simplicity. All units presented have been standardized and the coefficients altered accordingly. Thus downwelling shortwave and longwave fluxes, $SW\downarrow$ and $LW\downarrow$, and the solar constant, S_o, are in watts per square meter; the solar zenith angle Z is in degrees; the near-surface air temperature T is in kelvin, the near-surface vapor pressure e is in millibars, while the cloud optical depth τ, the surface albedo α, and the coefficients x, y and z, are unitless.

The Shortwave Clear Sky Flux

Lumb [1964] devised a formula suitable for hourly computations, as well as mean daily and monthly values, for estimating the shortwave flux over oceans

$$SW\downarrow_{\mathrm{clr}} = S_o \cos Z\,(0.61 + 0.20 \cos Z) \quad (1)$$

where S_O is the solar constant and Z is the solar zenith angle. It was derived from an extensive set of ship reports in the mid-Atlantic. Others have investigated Lumb's equation and found that the coefficients are sensitive to location; e.g., *Moritz* [1978] computed values to fit data from Baffin Bay, Canada.

Bennett [1982] used a very simple formula in an ice modeling experiment. *Ohmura* [1981], who used spring and summer data from Axel Heiberg Island, Canada, calculated the mean atmospheric transmittance to be 0.72, identical to the value used by Bennett, suggesting the equation used by Bennett may be reasonable for Arctic applications. This equation, due to its simplicity, would seem likely to be inaccurate over short time periods, although it may be good for estimating mean monthly values.

Zillman [1972] derived a parameterization using data from the Indian Ocean which include the near-surface vapor pressure e as an input variable:

$$SW\downarrow_{\mathrm{clr}} = (S_o \cos^2 Z) / [1.085 \cos Z + (2.7 + \cos Z)\times 10^{-3}\, e + 0.10]. \quad (2)$$

It has been used in sea ice modeling experiments [e.g., *Pease*, 1975; *Parkinson and Washington*, 1979]. *Shine* [1984] compared parameterized Arctic fluxes using this equation to fluxes generated by a radiative transfer model. He concluded that the Zillman equation generally underestimated Arctic fluxes and he modified the coefficients of the equation to give a better fit with the Arctic fluxes computed using the radiative transfer model. Other shortwave clear sky flux equations are given by *Moritz* [1978], *Bennett* [1982], and *Shine* [1984], respectively:

$$SW\downarrow_{\mathrm{clr}} = S_o \cos Z\,(0.47 + 0.47 \cos Z) \quad (3)$$

$$SW\downarrow_{\mathrm{clr}} = 0.72\, S_o \cos Z \quad (4)$$

$$SW\downarrow_{\mathrm{clr}} = (S_o \cos^2 Z) / [1.2 \cos Z + (1.0 + \cos Z)\times 10^{-3}\, e + 0.0455]. \quad (5)$$

The Shortwave All-Sky Flux

In order to parameterize the effects of clouds on the all-sky flux, $SW\downarrow_{\mathrm{clr}}$ multiplied by a simple cloud factor, which includes the cloud fraction and a coefficient, is commonly used. *Berliand* [1960] determined mean values of the coefficient according to latitude, where the coefficient equals 0.45 at 75°N/S:

$$SW\downarrow_{\mathrm{all}} = SW\downarrow_{\mathrm{clr}}\,(1 - 0.45\, c). \quad (6)$$

Berliand [1960] also devised a cloud factor c from mainly land surface observations, which has since been used extensively to estimate fluxes over both land and ocean areas:

$$SW\downarrow_{\mathrm{all}} = SW\downarrow_{\mathrm{clr}}\,(1 - x\,c - y\,c^2). \quad (7)$$

In this equation a quadratic dependence of the flux on cloud cover accounts for the relationship between cloud amount and cloud form. The idea behind this equation is that with an increase in cloudiness, the frequency of low clouds, which reduce solar radiation the most, is usually increased. Thus as cloudiness increases, the reduction of radiation occurs slowly at first and then more rapidly. *Budyko* [1974] investigated this equation and found a y coefficient of 0.38 to be good for all latitudes and assigned the x coefficient mean annual values according to latitude, where x is 0.14 at 85°, 0.41 at 55°, and 0.38 at 45°. *Bishop and Rossow* [1991] consider this parameterization better than those of *Reed* [1977] and *Dobson and Smith* [1988] over land surfaces, although both Reed, and Dobson and Smith consider this formula to poorly estimate fluxes over oceans.

Laevastu [1960] derived a shortwave cloud factor from midlatitude ocean data with a cubic function of fractional cloud cover which has since been used to estimate shortwave radiation in the sea ice modeling experiments of *Parkinson and Washington* [1979]:

$$SW\downarrow_{\mathrm{all}} = SW\downarrow_{\mathrm{clr}}\,(1 - 0.6\, c^3). \quad (8)$$

However, *Reed* [1977] found that this equation overestimates fluxes, except for high cloud amounts. *Tabata* [1964] derived a cloud factor to estimate fluxes over the oceans which includes the mean noon solar zenith angle Z_n and coefficients x and y, which were assigned values of 0.716 and 0.00252, respectively:

$$SW\downarrow_{\mathrm{all}} = SW\downarrow_{\mathrm{clr}}\,[1 - x\,c + y\,(90 - Z_n)]. \quad (9)$$

Reed [1977], *Dobson and Smith* [1988], *Simpson and Paulson* [1979], and *Isemer and Hasse* [1987] have also worked with Tabata's formulation, but none was for high-latitude conditions. A general problem with this equation is that by including the parameter Z_n, it is clearly of no use in estimating fluxes at timescales less than a day.

Lumb [1964], using Atlantic Ocean data, derived coefficients for a parameterization which varies according to cloud type and amount, for which nine categories of cloud type exist:

$$SW{\downarrow}_{\mathrm{all}} = S_o \cos Z\,(x + y \cos Z). \quad (10)$$

Reed [1977] found this equation to be quite accurate for eastern Pacific sites from the tropics to the Gulf of Alaska, and *Simpson and Paulson* [1979] considered the equation for mid-North Pacific Ocean fluxes to be better than those using the Reed formula. *Moritz* [1978], using data from Baffin Bay, Canada, recomputed values of the coefficients according to cloud level and opacity. Unfortunately, problems arise with the Lumb model since not all cloud observations fit one of the categories [*Dobson and Smith*, 1988] and because very reliable information on cloud type is necessary [*Reed*, 1977], which makes the equation less desirable. *Dobson and Smith* [1988] developed what they call the "cloud okta model" using ocean data based on the Lumb model. In this equation the coefficients are assigned values depending on the fractional cloud cover, and hence the flux does not depend on cloud type. They found that when measurements exist at a given location, allowing a calibration, this model does as well as the models of *Lumb* [1964] and *Reed* [1977]. *Bishop and Rossow* [1991], using temperate latitude ocean data, found that this model gives better results than the *Budyko* [1974] and *Reed* [1977] models.

Using the *Berliand* [1960] model, *Jacobs* [1978] arrived at a value of 0.33 for the coefficient based on measurements at Baffin Island, Canada, for the period June to October:

$$SW{\downarrow}_{\mathrm{all}} = SW{\downarrow}_{\mathrm{clr}}\,(1 - 0.33\,c). \quad (11)$$

Bennett [1982] used a value of 0.52 in Arctic sea ice modeling experiments:

$$SW{\downarrow}_{\mathrm{all}} = SW{\downarrow}_{\mathrm{clr}}\,(1 - 0.52\,c). \quad (12)$$

Shine [1984] developed a parameterization for estimating the flux under cloudy conditions to be suitable for high albedo surfaces such as snow and ice.

$$SW{\downarrow}_{\mathrm{cld}} = (53.5 + 1274.5 \cos Z) \cos^{0.5} Z \,/\, [1 + 0.139\,(1 - 0.9345\,\alpha)\tau] \quad (13a)$$

$$SW{\downarrow}_{\mathrm{all}} = [(1 - c)\,SW{\downarrow}_{\mathrm{clr}} + (c)\,SW{\downarrow}_{\mathrm{cld}}] \quad (13b)$$

The inclusion of the cloud optical depth τ and ground surface albedo α takes into account the effects of cloud thickness and multiple reflections between the surface and cloud base. This equation is likely to be superior to the others described, particularly for estimating fluxes over short time periods.

The Longwave Clear Sky Flux

Ångström [1918] derived a method of estimating the downwelling longwave clear sky flux in which the atmospheric emittance is parameterized as a function of the near-surface vapor pressure:

$$LW{\downarrow}_{\mathrm{clr}} = \sigma T^4\,(x - 10^{-ze}\,y). \quad (14)$$

where T is the near-surface air temperature and is the Stefan-Boltzmann constant. *Idso and Jackson* [1969] report that the empirical coefficients are somewhat variable by region and others, e.g. *Budyko* [1974], have arrived at different values for the coefficients. *Brunt* [1932] devised a formula which also includes the near-surface vapor pressure and coefficients:

$$LW{\downarrow}_{\mathrm{clr}} = \sigma T^4\,(x + y\,e^{0.5}). \quad (15)$$

He assigned values of 0.526 and 0.075 to x and y. Several others have since found the form of the equation good but have assigned different values to the coefficients; e.g., *Berliand and Berliand* [1952] used $x = 0.61$ and $y = 0.058$. *Arnfield* [1979] examined a wide range of coefficients and concluded that the performance of the model varied considerably. *Marshunova* [1966] attributed the many different values of the coefficients to differences in measuring devices and in geographic conditions. Marshunova determined coefficients for various coastal Arctic stations and for drifting ice stations for year-round data over 5 years, with a mean annual temperature range of approximately 235-280 K. She found x to vary between 0.605 and 0.695 and y to vary between 0.078 and 0.040 for coastal stations and found x and y to average 0.67 and 0.05, respectively, for the drifting stations:

$$LW{\downarrow}_{\mathrm{clr}} = \sigma T^4\,(0.67 + 0.05\,e^{0.5}). \quad (16)$$

Efimova [1961], using year-round land data from many Russian stations, modified the form of *Brunt's* [1932] formula to be more accurate under conditions of low absolute humidity, claiming that using $e^{0.5}$ resulted in fluxes too low for regions of low humidity:

$$LW{\downarrow}_{\mathrm{clr}} = \sigma T^4\,(0.746 + 0.0066\,e) \quad (17)$$

Swinbank [1963], using data from Australia, the Indian Ocean at low latitudes, England and France, for a temperature range of approximately 275-302 K, derived two parameterizations:

$$LW{\downarrow}_{\mathrm{clr}} = 1.195\,\sigma T^4 - 170.9 \quad (18)$$

$$LW{\downarrow}_{\mathrm{clr}} = \sigma T^4\,(9.365{\times}10^{-6}\,T^2). \quad (19)$$

He considered the differences between the two insignificant, although the second to have a more physical basis. *Maykut and Church* [1973] report some reasonable success with this scheme at the lower latitudes but not at high latitudes, and *Jacobs* [1978] claims that the formula underestimates fluxes at Baffin Island, Canada. *Zillman* [1972], however, using Southern Ocean data, computes a coefficient for one of the Swinbank equations which matches quite closely that used by Swinbank

$$LW{\downarrow}_{\mathrm{clr}} = \sigma T^4\,(9.2{\times}10^{-6}\,T^2), \quad (20)$$

and which has been used by *Pease* [1975] for modeling Antarctic sea ice. *Idso and Jackson* [1969] consider the equation of Swinbank to be more general than the *Ångström* [1918] and *Brunt* [1932] formulas but still lacking universal applicability:

$$LW{\downarrow}_{\mathrm{clr}} = \sigma T^4\,[1 - 0.261 \exp\{-7.77{\times}10^{-4}\,(273 - T)^2\}]. \quad (21)$$

Idso and Jackson [1969] have developed a slightly more complex relationship but one which treats the atmospheric emittance as a function of near-surface temperature alone. The parameterized fluxes fit well data from Alaska, Arizona, Australia, and the Indian Ocean over a total temperature range of 244-310 K and should be valid for all latitudes and seasons. The formula was found to perform marginally better than that of *Swinbank* [1963] for southern Ontario summer data by *Arnfield* [1979] and has been used in ice modeling experiments by *Parkinson and Washington* [1979]. It appears, however, to underestimate Arctic fluxes at Baffin Island according to *Jacobs* [1978].

Maykut and Church [1973], using Arctic data collected at Barrow, Alaska, over a 5-year period with a mean annual temperature range of 244-277 K, derive a simple formula where the atmospheric emittance is based on a single coefficient:

$$LW{\downarrow}_{clr} = 0.7855\,\sigma T^4 . \quad (22)$$

Ohmura [1981] derives a formula to best fit Arctic observations during the spring and summer from Axel Heiberg Island, Canada, over a temperature range of 243-289 K, which includes the near-surface temperature in the parameterization of the atmospheric emittance:

$$LW{\downarrow}_{clr} = \sigma T^4\,(8.733\times10^{-3}\,T^{0.788}) . \quad (23)$$

Idso [1981] derived a formula from observations made at Phoenix, Arizona, for temperatures greater than 285 K, which includes both the near-surface temperature and near-surface vapor pressure as input parameters:

$$LW{\downarrow}_{clr} = \sigma T^4\,(0.70 + 5.95\times10^{-5}\,e^{1500/T}) \quad (24)$$

Andreas and Ackley [1982] have modified a coefficient in the formula in order for it to be appropriate for the Arctic and Antarctic regions since aerosol concentrations are suspected to be lower over the oceans and the polar regions than at Arizona:

$$LW{\downarrow}_{clr} = \sigma T^4\,(0.601 + 5.95\times10^{-5}\,e^{1500/T}) \quad (25)$$

The Longwave All-Sky Flux

Marshunova [1966] used a cloud factor that includes the fractional cloud cover and a coefficient to parameterize Arctic fluxes:

$$LW{\downarrow}_{all} = LW{\downarrow}_{clr}\,(1 + x\,c). \quad (26)$$

Values of the coefficient were derived using year-round Arctic data covering a temperature range of approximately 235-280 K. The coefficient varies by season and time. Extreme values for Arctic coastal stations range from 0.16 in summer to 0.31 in winter, indicating that clouds have a lesser relative impact on the longwave flux in summer than in winter, although the absolute effects are similar. Drifting station values vary from 0.22 in summer to 0.30 in winter. *Jacobs* [1978] arrived at a mean value of 0.26 for the coefficient in a cloud factor of the same type using data from Baffin Island, Canada, for the period June - December:

$$LW{\downarrow}_{all} = LW{\downarrow}_{clr}\,(1 + 0.26\,c). \quad (27)$$

Jacobs found little variation in its value between summer and winter.

Budyko [1974] suggested a different cloud factor, showing that the increase in the flux with an increase in cloudiness is not linear but, instead, an exponential function of cloud amount, or c^y. *Boltz* [1949] varied x according to the cloud type and used a y value of 2. This type of cloud factor may be more accurate when cloud type is known, although cloud type is a subjective judgement:

$$LW{\downarrow}_{all} = LW{\downarrow}_{clr}\,(1 + x\,c^2) \quad (28)$$

Maykut and Church [1973], who used year-round data collected at Barrow, Alaska, over the temperature range 244-277 K, arrived at values for x and y of 0.223 and 2.75:

$$LW{\downarrow}_{all} = LW{\downarrow}_{clr}\,(1 + 0.22\,c^{2.75}). \quad (29)$$

Zillman [1972] treats the cloud effects a different way, where the cloud factor is considered a function of both the fractional cloud cover and the near-surface temperature. Zillman developed this equation using data from southern oceans, and it has been used by *Pease* [1975] in Antarctic sea ice modeling experiments:

$$LW{\downarrow}_{all} = LW{\downarrow}_{clr} + \sigma T^4\,0.96\,(1 - 9.2\times10^{-6}\,T^2)\,c . \quad (30)$$

None of these equations treats adequately, or at all, the effects of variable cloud base height, cloud thickness, or cloud water phase. Their accuracy is therefore likely to be limited, particularly for estimating fluxes over short timescales. There is yet another parameterization for downwelling longwave fluxes that deserves mention, one that takes into account cloud properties. The parameterization of *Schmetz et al.* [1986] was also investigated. The all-sky flux parameterization consists of a parameterization for the clear sky flux plus a parameterization for the cloud contribution flux:

$$LW{\downarrow}_{all} = LW{\downarrow}_{clr} + (1 - \varepsilon_0)\,c\,\varepsilon_c\,\sigma\,T_0^4\,\exp\,[(T_B + T_0)\,/\,46]$$

where ε_0 is the effective sky emittance, ε_c is the cloud emissivity, T_0 is the near-surface air temperature, and T_B is the cloud base temperature. This scheme performs well under both winter and summer conditions and for a wide range of atmospheric emissivities. The parameterization is therefore anticipated to be reasonably accurate under almost all Arctic conditions and a significant improvement upon simpler parameterizations that only consider the cloud fraction as a variable. However, because its use requires information that is not generally available, i.e., cloud base height, it is not considered further in this study.

Comparisons With In Situ Measurements

In this section, measurements of climatological variables from Resolute, Northwest Territories, Canada and Barrow, Alaska, are used in the various parameterizations, and the estimated fluxes are compared to the in situ measurements. The Resolute observations were made at the Seasonal Sea Ice Monitoring and Modelling Site (SIMMS), located off the coast of Corwallis Island near Resolute, 74.6°N, 94.7°W (Figure 1) [*Papakyriakou*, 1993]. It is a region where both multiyear and first-year ice can be found, as well as areas of open water in the summer. Downwelling and upwelling shortwave and longwave radiation were measured at the site and averaged over 15-min intervals. Data from May and June 1993 are used here. While these data cover a wide range of solar zenith angles, no part of this period was without solar radiation.

The Barrow data were collected at the Climate Monitoring and Diagnostic Laboratory (CMDL) baseline observatory (71.32°N,156.61°W) near Barrow, Alaska (BRW) (Figure 1). Downwelling and upwelling shortwave and longwave radiation are measured continuously at BRW (refer to *Peterson and Rosson* [1994] and earlier National Oceanic and Atmospheric Administration (NOAA)/CMDL annual reports for details). Although situated on the Arctic tundra, where complete melting of the snow occurs each summer, the site is generally considered to be representative of an Arctic maritime climate because the prevailing winds are northeasterly, off the Beaufort Sea; all observations are made within 2 km of the coast. It is a very cloudy region and one of high relative humidity. Surface albedo varies from about 0.18 during summer months to over 0.86 when snow covered. BRW radiation data are collected at a sampling rate of 1 Hz but averaged into 3-min raw voltage or resistance values. The data used in this study have been carefully edited, calibrated, and further averaged into daily values (see R.S. Stone et al., Barrow Surface Radiation Balance Measurements, January 1992 to December 1994, NOAA data report ERL, in preparation, 1996]. Shortwave irradiance measurements are accurate to within 3%, on average, with systematically greater uncertainties as the signal diminishes with increasing zenith angle. The longwave data have been shown to be accurate to within about 1% [*Dutton*, 1993]. Daily data from the entire 1994 year are used here.

Each of these data sets was analyzed separately in order to examine the effects of the differences in surface types/location and time averaging. Results for the two data sets were nearly identical, with the accuracy ranking of the various parameterizations being the same and the means and root-mean-square errors (RMSE) within 10% for the longwave and 20% percent for the shortwave. This result is significant, given that high temporal resolution data are often not available or desired in modeling studies. In the figures and tables presented hereafter, the results for these two data sets are combined.

For the *Shine* [1984] parameterization, cloud optical depth is required. Values of cloud optical depth were not measured at either site but were, instead, estimated by inverting a radiative transfer model using the method of *Leontyeva and Stamnes* [1994] and a two-stream model [see *Key*, 1994, and references therein]. Downwelling shortwave fluxes were computed over a range of optical depth for the surface and atmospheric conditions observed. The optical depth for each observation was the value that gave the best match between that modeled flux and the observed flux. Since using these optical depths in the parameterization is somewhat circular, we instead used the mean of all 0.6-μm optical depths for the calculations. The mean optical depth was approximately 8.

Only those parameterizations with coefficients derived specifically for the polar regions and parameterizations derived for use over the whole globe are used in subsequent analyses. The parameterizations investigated are (3), (4), and (5) for the shortwave clear sky flux; (6), (11), (12), and (13b) for the shortwave all-sky flux; (16), (17), (20), (21), (22), (23), and (25) for the longwave clear sky flux; and (27), (29), and (30) for the longwave cloudy sky flux. The longwave and shortwave all-sky parameterizations include a cloud factor multiplied by $SW{\downarrow}_{clr}$ or $LW{\downarrow}_{clr}$. Since $SW{\downarrow}_{clr}$ cannot be measured under cloudy skies, values need to be estimated. *Shine*'s [1984] $SW{\downarrow}_{clr}$ is used to estimate the shortwave clear sky flux since the results of this study show this to be the most accurate parameterization for this data set. In a similar manner, the longwave flux under clear skies is parameterized using *Efimova* [1961] to estimate the clear sky component since this is shown to be the most accurate parameterization of the clear sky longwave flux. The longwave cloudy sky parameterization of *Marshunova* [1966], which includes a spatially and temporally variable coefficient, is not considered here because it is essentially the same as that of *Jacobs* [1978].

Table 2. Parameterized Shortwave Clear Sky Flux Errors

	Mean	Mean Error	RMSE
Measured Flux	430.7		
Moritz [1978]	395.9	-34.8 (-8.1)	40.1
Bennett [1982]	409.9	-20.8 (-4.8)	36.1
Shine [1984]	435.8	5.1 (1.2)	18.6

Values are in watts per square meter. RMSE is root-mean-square error. Numbers in parentheses are percentages.

Results: Shortwave Fluxes

For comparison with the Resolute data, shortwave flux parameterizations are computed using the solar zenith angle in the middle of the 15-min data-averaging period. For the daily Barrow data, fluxes are computed for each hour of the day using the solar zenith angle in the middle of the hour. The 24 flux values are then averaged to get the daily average flux.

Parameterized shortwave flux errors under clear skies are shown in Figure 2. The mean, mean error, and RMSE of the parameterized fluxes are given in Table 2. The most accurately parameterization of $SW{\downarrow}_{clr}$ is that of *Shine* [1984]. The measured flux typically varies by approximately 50 W m^{-2} or more for each

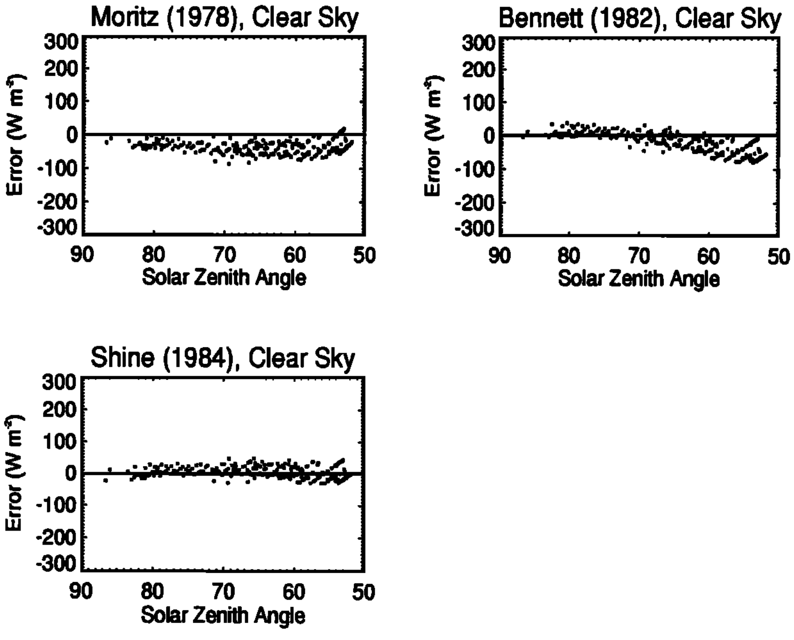

Figure 2. The shortwave clear sky flux error for three parameterizations (estimated flux minus the flux measured at Barrow and Resolute).

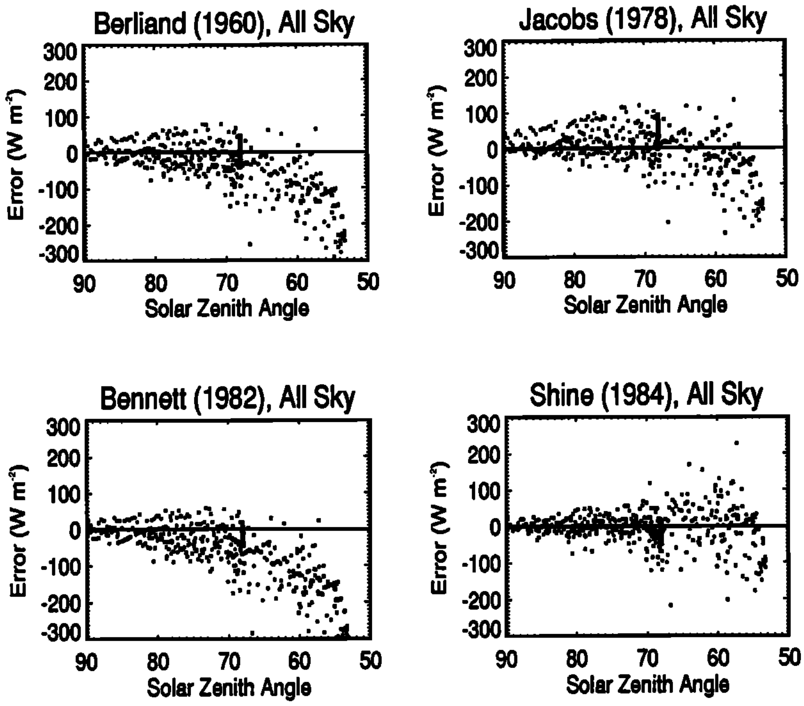

Figure 3. The shortwave all-sky flux error for four parameterizations (estimated flux minus the flux measured at Barrow and Resolute).

Sun angle. This variability does not exist in any of the parameterized fluxes. Some of the variability may be due to measurement errors (5%). However, other factors are probably important, e.g., tropospheric aerosols. The equation of *Bennett* [1982] tends to overestimate fluxes at low Sun angles and underestimate fluxes at higher Sun angles but performs surprisingly well, considering its simplicity. The parameterized fluxes using *Moritz* [1978] are the least accurate. The equation tends to underestimates fluxes, particularly under moderate solar zenith angles.

Parameterized shortwave flux errors under all skies are shown in Figure 3. The mean, mean error, and RMSE of the parameterized fluxes are given in Table 3. The most accurately parameterized fluxes are those using *Shine* [1984]. The parameterization includes surface albedo and cloud optical depth parameters. Since the cloud optical depths were derived, not measured, this result is not totally unexpected. The parameterizations of *Berliand* [1960], *Jacobs* [1978], and *Bennett* [1982] are extremely simple, consisting of a coefficient multiplied by the clear sky flux. Thus they do not model any of the variability due to factors such as cloud thickness or surface albedo. The parameterizations of Berliand and Bennett both significantly underestimates fluxes. The parameterization of Jacobs fares better, perhaps since the coefficient was selected to fit Canadian Arctic data. Although the RMSE is still very high, the mean error is reasonably small.

Table 3. Parameterized Shortwave All-Sky Flux Errors

	Mean	Mean Error	RMSE
Measured Flux	214.6		
Berliand [1960]	176.9	-37.7 (-17.6)	78.4
Jacobs [1978]	211.1	-3.6 (-1.7)	55.1
Bennett [1982]	157.1	-57.6 (-26.8)	97.8
Shine [1984]	211.5	-3.2 (-1.5)	46.3

See Table 2 footnote.

Results: Longwave Fluxes

Parameterized longwave flux errors under clear skies are shown in Figure 4. The mean, mean error, and RMSE of the parameterized fluxes are given in Table 4. The most accurately parameterized fluxes are those using *Efimova* [1961]. This equation was not developed using Arctic data but was designed to be accurate in regions of low absolute humidity, which Resolute typifies. The parameterized fluxes of Idso and *Jackson* [1969] are almost as accurate as those of Efimova. The parameterizations developed using observed ground-based Arctic data, i.e., *Marshunova* [1966], *Maykut and Church* [1973] and *Ohmura* [1981], also give moderately accurate results. The parameterizations of *Zillman* [1972] and *Andreas and Ackley* [1982] are less accurate. The accuracy/inaccuracy of the equations appears to be largely due to the coefficients chosen rather than their form. It

Table 4. Parameterized Longwave Clear Sky Flux Errors

	Mean	Mean Error	RMSE
Measured Flux	214.2		
Efimova [1961]	214.3	0.1 (0.04)	7.8
Marshunova [1966]	201.1	-13.1 (-6.1)	15.7
Idso and Jackson [1969]	215.9	1.6 (0.8)	13.3
Zillman [1972]	188.0	-26.2 (-12.3)	27.5
Maykut and Church [1973]	224.7	10.5 (4.9)	12.9
Ohmura [1981]	204.1	-10.1 (-4.7)	12.5
Andreas and Ackley [1982]	213.9	-42.0 (-19.6)	43.4

See Table 2 footnote.

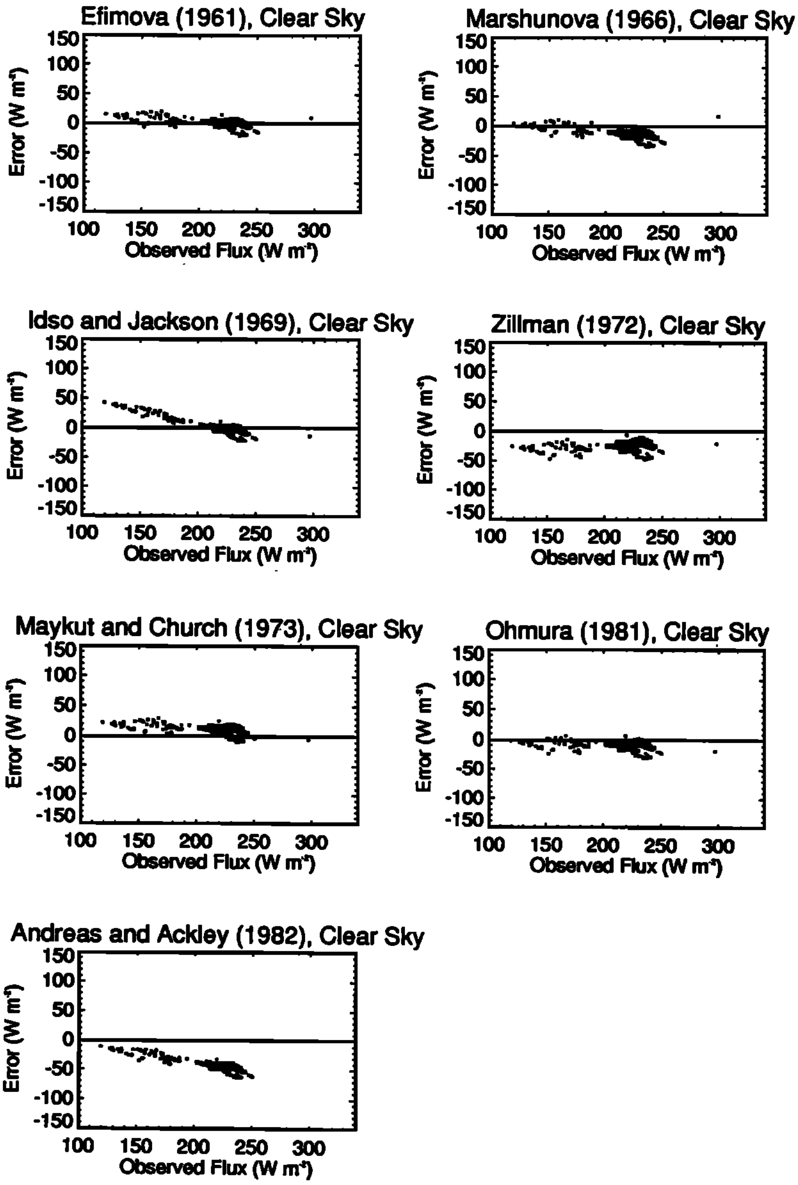

Figure 4. The longwave clear sky flux error as a function of the observed flux for seven parameterizations (estimated flux minus the flux measured at Barrow and Resolute).

appears that none of the equations models effectively the observed variability of the flux due to factors other than near-surface temperature variations.

Parameterized longwave flux errors under all skies are shown in Figure 5. The mean, mean error and RMSE of the parameterized fluxes are given in Table 5. The most accurately parameterized fluxes are those using *Jacobs* [1978]. The errors may be due, in part, to errors in the clear sky flux parameter (that of *Efimova* [1961]), which is merely an estimate. Other errors are very likely caused by atmospheric factors that are not accounted for in the equation such as cloud base height. The *Jacobs* [1978] equation is not surprisingly the most accurate since it was developed using Arctic data, unlike that of *Zillman* [1972]. The parameterized fluxes using *Zillman* [1972] tend to overestimate the observed flux. Once again, a modification of the coefficients would be expected to produce more accurate fluxes.

Table 5. Parameterized Longwave All-Sky Flux Errors

	Mean	Mean Error	RMSE
Measured Flux	267.2		
Zillman [1972]	299.8	32.6 (12.2)	36.6
Maykut and Church [1973]	257.5	-9.7 (-3.6)	18.7
Jacobs [1978]	267.9	0.7 (0.3)	16.9

See Table 2 footnote.

Preferred All-Sky Parameterizations

The results from the investigation using the in situ data show the most accurate parameterizations to be those of *Shine* [1984] for $SW{\downarrow}_{clr}$ and $SW{\downarrow}_{cld}$ and those of *Efimova* [1961] for $LW{\downarrow}_{clr}$ and *Jacobs* [1978] for $LW{\downarrow}_{cld}$. The shortwave all-sky parameterization of *Jacobs* [1978] and the longwave all-sky parameterization of *Maykut and Church* [1973] also performed very well. The

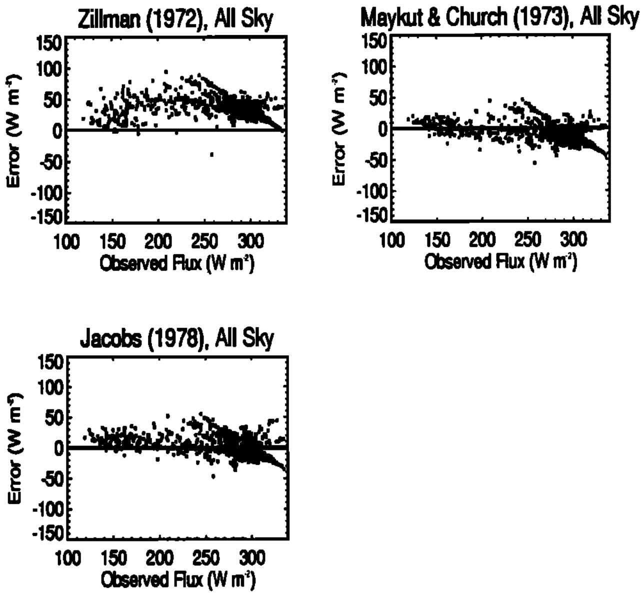

Figure 5. The longwave all-sky flux error as a function of the observed longwave flux for three parameterizations (estimated flux minus the flux measured at Barrow and Resolute).

preferred parameterization for $SW\downarrow_{all}$ is derived by combining the clear and cloudy sky equations of *Shine* [1984, equations (5) and (13a)], which is given as (13b). These are identical to those used by *Shine and Crane* [1984] and *Shine and Henderson-Sellers* [1985].

The preferred parameterization of $LW\downarrow_{all}$ is derived by using *Efimova* [1961] for $LW\downarrow_{clr}$ in *Jacobs* [1978] for $LW\downarrow_{all}$:

$$LW\downarrow_{all} = \sigma T^4 \, (0.746 + 0.0066\, e) \;\; (1 + 0.26c) \qquad (31)$$

These parameterization schemes are recommended for use in sea ice models, although there are, of course, uncertainties in their suitability for estimating fluxes under conditions different from those measured at Barrow and Resolute. The shortwave flux parameterization of *Shine* [1984] has been used in a number of Arctic ice modeling experiments. *Shine and Henderson-Sellers* [1985], for example, investigated the sensitivity of a one-dimensional thermodynamic sea ice model to changes in surface albedo. The recommended longwave flux parameterization has not yet been used in ice modeling experiments.

Comparison of All-Sky Radiative Flux Climatologies

Perhaps the most comprehensive climatology of the shortwave all-sky flux generated using ground-based measurements is that of *Vowinckel and Orvig* [1962], developed using data collected from Greenland, Canada, Alaska, Russia, Scandinavia and the central Arctic during various periods over the last 50 years. *Marshunova* [1966] has also generated an Arctic flux climatology from ground-based observations, tabulating monthly shortwave and longwave all-sky fluxes from Russian coastal stations, ships, and drifting ice stations in the central Arctic.

Schweiger and Key [1994] calculated mean monthly Arctic Ocean radiative fluxes and cloud forcing effects for the period 1983-1990 using the monthly cloud product of the International Satellite Cloud Climatology Project. The monthly (C2) product contains global information on satellite-derived cloud fraction, atmospheric temperature, water vapor and ozone, surface temperature and reflectivity, cloud top pressure and temperature, and cloud optical depth. The atmospheric variables are averages for approximately 280 x 280 km cells [*Rossow and Schiffer*, 1991]. The ISCCP C2 data set provides an extensive set of input data for the radiative flux parameterizations being investigated in this study, although there are uncertainties in the accuracy of the data. The satellite cloud amounts were found to be typically 5% lower in winter and up to 35% lower in summer than surface observations over the Arctic [*Schweiger and Key*, 1992]. To estimate surface radiative fluxes, a two-stream radiative transfer model with 24 shortwave and 105 longwave bands was employed. The clear and cloudy portions of each cell were treated separately, and the all-sky fluxes were computed as the sum of the clear and cloudy sky fluxes weighted by the cloud fraction. This set of fluxes is hereafter referred to as the radiative transfer model (RTM) fluxes.

The Arctic flux "climatologies" developed using the parameterizations for all-sky conditions (equations (13b) and (31)) are compared to the climatologies of *Vowinckel and Orvig* [1962], *Marshunova* [1966], and *Schweiger and Key* [1994] for the shortwave all-sky flux, and compared with the climatologies of Marshunova, and Schweiger and Key for the longwave all-sky flux. The climatologies are generated with five years of data (1984-1988) for the months of January, April, July, and October at the nine Arctic locations shown in Figure 1. These locations were subjectively chosen to capture the spatial diversity of the Arctic surface radiation field. The ISCCP satellite data, including the cloud fractions, are used as input.

Fluxes from the *Vowinckel and Orvig* [1962] climatology for the areas corresponding to the nine locations are estimated through interpolation of their isoline maps. Because the isolines are drawn at intervals of approximately 10 W m^{-2}, the errors should be no greater than this. The shortwave fluxes of *Marshunova* [1966] corresponding to the particular locations are estimated from gridded data for areas north of 75° and from ship measurements. The longwave fluxes corresponding to the particular locations are estimated by interpolating between coastal measurements and by averaging values from drifting stations in the central ice pack. Owing to the limited spatial coverage of Marshunova's data, reasonable estimates of fluxes are not possible for some of the locations. Hence shortwave fluxes are only estimated for locations 1, 2, 6, 8, and 9, and longwave fluxes are only estimated for locations 1, 6, 8, and 9. These estimated fluxes may be less accurate than those estimated from the charts of *Vowinckel and Orvig* [1962].

Table 6 gives the mean monthly shortwave all-sky fluxes averaged over the nine Arctic locations. The climatologies of *Vowinckel and Orvig* [1962] and *Marshunova* [1966] are in close agreement (generally within 5 W m^{-2}) which gives us some confidence in their reliability and usefulness for comparative purposes. There are, however, considerable discrepancies between these climatologies and the RTM climatology, where differences generally exceed 20 W m^{-2}.

The parameterized shortwave all-sky fluxes are considerably lower for April than the other flux climatologies, generally by 10-60 W m^{-2}. This large difference is due to the very low parameterized fluxes under cloudy skies using the formula of *Shine* [1984]. The low values may be due, at least in part, to large values of cloud optical depth in the ISCCP data set for this month (averaging approximately 40). The RTM fluxes, calculated using the same data set, are, however, in somewhat closer agreement with the fluxes of *Vowinckel and Orvig* [1962] and *Marshunova* [1966], which may indicate that the parameterization of cloud effects by Shine is not accurate for the early spring. In July the parameterized fluxes are again lower than the RTM fluxes, due to the low

Table 6. Mean Shortwave Fluxes for Locations in Figure 1

	January	April	July	October
Parameterized Fluxes using *Shine* [1984] with ISCCP data	0.0 (0.0)	107.6 (107.9)	231.9 (243.8)	4.8 (6.2)
RTM Fluxes with ISCCP data	0.0 (0.0)	132.3 (140.2)	258.3 (279.5)	6.0 (8.1)
Measured Fluxes of *Vowinckel and Orvig* [1962]	0.0 (0.0)	155.8 (160.6)	205.6 (208.0)	12.1 (11.8)
Measured Fluxes of *Marshunova* [1966]	- (0.0)	- (155.6)	- (206.7)	- (12.6)

Values are in watts per square meter. Numbers in first row are for locations 1-9, while those in parentheses are for locations 1, 2, 6, 8, and 9. ISCCP is the International Satellite Cloud Climatology Project. RTM is radiative transfer model.

parameterized values of the cloudy sky flux. The fluxes are higher than those of Marshunova and Vowinckel and Orvig, which indicates that the input data may be inaccurate for midsummer.

Table 7 gives the mean monthly longwave all-sky fluxes averaged over the nine Arctic locations. The climatologies are generally in closer agreement for the all-sky longwave flux than for the all-sky shortwave flux. The largest discrepancies are between the climatology of *Marshunova* [1966] and the RTM climatology during summer, with the RTM fluxes being considerably lower. These discrepancies are probably due to inaccuracies in the ISCCP cloud amounts and optical depths.

The parameterized fluxes are higher than the RTM fluxes for all months by approximately 15-20 W m^{-2} but are lower than those of *Marshunova* [1966] for all months, except January. The annual flux range of the parameterized flux climatology is therefore smaller than that of Marshunova by approximately 40-45 W m^2. It is uncertain whether these discrepancies are the result of inaccurate ISCCP data, a poor parameterization, or errors associated with estimating fluxes from Marshunova's tables for the particular locations.

Summary and Conclusions

Downwelling longwave and shortwave radiative fluxes for use in sea ice models are commonly generated in one of three ways.

1. Fluxes may be prescribed from existing climatologies. *Maykut and Untersteiner* [1971] and *Semtner* [1976], for example, simulate the Arctic ice pack by prescribing spatially invariant monthly fluxes according to the Arctic climatology developed by *Marshunova* [1966]. With the ever-increasing availability of Arctic cloud and surface data, significant improvements to this approach are now possible.
2. Spatially and temporally variable fluxes may be generated using simple parameterizations such as the ones described here. Many such ice modeling experiments have been performed [e.g., *Parkinson and Washington*, 1979; *Andreas and Ackley*, 1981; *Bennett*, 1982; *Shine and Crane*, 1984].
3. Fluxes may be calculated using radiative transfer models. This technique has been explored recently by *Curry and Ebert* [1993] and *Maslanik et al.* [1995]. However, for dynamic-thermodynamic models the computational burden is excessive and simpler parameterization schemes are desirable.

The objectives of this study were to use ground-based measurements to identify the most accurate parameterizations of downwelling shortwave and longwave radiative fluxes at the Arctic surface under both clear and cloudy skies and to develop shortwave and longwave all-sky parameterizations. Comparison of the parameterized fluxes computed using input data measured at Barrow and Resolute with measured fluxes shows that the shortwave fluxes for clear and cloudy skies are most accurately estimated using the parameterizations of *Shine* [1984], the longwave flux for clear skies is most accurately estimated using the parameterization of *Efimova* [1961], and the longwave flux for cloudy skies is most accurately estimated using the parameterization of *Jacobs* [1978].

Fluxes computed using these parameterizations and the ISCCP monthly cloud product as input were compared to climatologies. Differences between the parameterized fluxes and the climatologies of *Vowinckel and Orvig* [1962], *Marshunova* [1966], and *Schweiger and Key* [1994] were large in the shortwave but small in the longwave.

The shortwave all-sky equations of *Shine* [1984], and the longwave all-sky equations of *Efimova* [1961] and *Jacobs* [1978] are tentatively recommended for estimating radiative fluxes in sea ice models. Further work is needed to investigate in more detail parameterizations of the shortwave cloudy sky flux. Refinement of coefficients in a number of the equations, as well as the inclu-

Table 7. Mean Longwave Fluxes for Locations in Figure 1

	January	April	July	October
Parameterized Fluxes using *Efimova* [1961] and *Jacobs* [1978] with ISCCP data	206.3 (187.8)	209.6 (192.0)	292.0 (285.3)	243.2 (223.9)
RTM Fluxes with ISCCP data	189.8 (173.2)	187.3 (170.8)	279.0 (272.6)	223.3 (205.2)
Measured Fluxes of *Marshunova* [1966]	- (169.8)	- (197.8)	- (311.0)	- (238.8)

See Table 6 footnote.

sion of other parameters (e.g., atmospheric aerosol amount, cloud microphysics), may yield better results.

Acknowledgments. This research was funded by NASA grant NAGW-2407 and NSF grant OPP-9321547 and is based on R. Silcox's thesis work. Thanks are due to NOAA/CMDL for providing the Barrow data, R.G. Barry for many helpful discussions, and J. Maslanik for ice model runs.

References

Andreas, E. L., and S. F. Ackley, On the differences in ablation seasons of Arctic and Antarctic sea ice, *J. Atmos. Sci.*, *39*, 440-447, 1982.

Ångström, A., A study of the radiation of the atmosphere, *Smithson. Misc. Collect.*, *65*, 3, 1918.

Arnfield, A. J., Evaluation of empirical expressions for the estimation of hourly and daily totals of atmospheric longwave emission under all-sky conditions, *Q. J. R. Meteorol. Soc.*, *105*, 1041-1052, 1979.

Bennett, T. J., A coupled atmosphere-sea ice model study of the role of sea ice in climatic predictability, *J. Atmos. Sci.*, *39*, 1456-1465, 1982.

Berliand, T. C., Method of climatological estimation of global radiation, *Meteorol. Gidrol.*, *6*, 9-12, 1960.

Berliand, M. E., and T. G. Berliand, Determining the net long-wave radiation of the Earth with consideration of the effects of cloudiness, *Izv. Akad. Nauk SSSR Ser. Geofiz.*, *1*, 1952.

Bishop, J. K. B., and W. B. Rossow, Spatial and temporal variability of global surface solar irradiance, *J. Geophys. Res.*, *96*, 16,839-16, 858, 1991.

Boltz, H. M., Die Abhängigkeit der infraroten Gegenstrahlung von der Bewölkung, *Z. F. Meteorol.*, *3*, 201-203, 1949.

Brunt, D., Notes on radiation in the atmosphere, *Q. J. R. Meteorol. Soc.*, *58*, 389-420, 1932.

Budyko, M. I., *Climate and Life*, Academic, San Diego, Calif., 1974.

Curry, J. A. and E. E. Ebert, An intermediate one-dimensional thermodynamic sea ice model for investigating ice-atmosphere interactions, *J. Geophys. Res.*, *98*, 10,085-10,109, 1993.

Dobson, F. W. and S. D. Smith, Bulk models of solar radiation at sea, *Q. J. R. Meteorol. Soc.*, *114*, 165-182, 1988.

Dutton, E.G., An extended comparison between LOWTRAN7 computed and observed broadband thermal irradiances: Global extreme and imtermediate surface conditions, *J. Atmos. Oceanic Technol.* *10*(3), 326-336, 1993.

Efimova, N. A., On methods of calculating monthly values of net longwave radiation, *Meteorol. Gidrol.*, *10*, 28-33, 1961.

Idso, S. B., A set of equations for full spectrum and 8-14 microns and 10.5-12.5 microns thermal radiation from cloudless skies, *Water Resour. Res.*, *17*, 295-304, 1981.

Idso, S. B., and R. D. Jackson, Thermal radiation from the atmosphere, *J. Geophys. Res.*, *74*, 5397-5403, 1969.

Isemer, H.-J., and L. Hasse, *The Bunker Climate Atlas of the North Atlantic Ocean*, vol.2: *Air-Sea Interactions*, 252 pp., Springer-Verlag, New York, 1987.

Jacobs, J. D., Radiation climate of Broughton Island, Energy budget studies in relation to fast-ice breakup processes in Davis Strait, edited by R.G. Barry and J. D. Jacobs, *Occas. Pap. 26*, pp. 105-120, INst. of Arctic and Alp. Res., Univ. of Colo., Boulder, 1978.

Key, J. R., Streamer, version 2.0p: Users guide, 70 pp., Coop. Inst. for Res. in Environ. Sci., Univ. of Colo., Boulder, 1994.

Konzelmann, T., R. S. W. van de Wal, W. Greuell, R. Bintanja, E. A. C. Henneken, and A. Abe-Ouchi, Parameterization of global and longwave incoming radiation for the Greenland Ice Sheet, *Global Planet. Change*, *9*, 143-164, 1994.

Laevastu, T., Factors affecting the temperature of the surface layer of the sea, *Commentat. Phys. Math.*, *25*, 1, 1960.

Leontyeva, E., and K. Stamnes, Estimations of cloud optical thickness from ground-based measurements of incoming solar radiation in the Arctic, *J. Clim.*, *7*, 566-578, 1994.

Lumb, F. E., The influence of cloud on hourly amounts of totalradiation of the sea surface, *Q. J. R. Meteorol. Soc.*, *90*, 43-56, 1964.

Marshunova, M. S., Principal characteristics of the radiation balance of the underlying surface, edited by J.O. Fletcher et al., *Soviet Data on the Arctic Heat Budget and Its Climate Influence*, Rep. *R.M.5003-PR*, Rand Corp., Santa Monica, Calif., 1966.

Maslanik, J.A., J. Key, and A.S. Schweiger, Cloud amount and radiation: Effects of climatology and method on Arctic sea ice simulations, paper presented at Fourth Conference on Polar Meteorology and Oceanography, Am. Meteorol. Soc., Dallas, January 1995.

Maykut, G. A. and P. E. Church, Radiation climate of Barrow, Alaska, 1962-66, *J. Appl. Meteorol.*, *12*, 620-628, 1973.

Maykut, G.A. and N. Untersteiner, Some results from a time-dependent thermodynamic model of sea ice, *J. Geophys. Res.*, *76*, 1550-1575, 1971.

Moritz, R. E., A model for estimating global solar radiation, Energy budget studies in relation to fast-ice breakup processes in Davis Strait, edited by R.G. Barry and J. D. Jacobs, *Occas.l Pap. 26*, pp. 121-142, Inst. of Arctic and Alp. Res., Univ. of Colo., Boulder, 1978.

Ohmura, A., Climate and energy balance of the Arctic tundra, *Zürcher Geogr. Schr. 3*, 448 pp., Geogr. Inst., Zürich, Switzerland, 1981.

Papakyriakou,T., Micrometeorology, *SIMMS93 Data Report*, edited by K.M. Misurak, D. G. Barber and E. F. LeDrew, Earth Obs. Lab., Inst. for Space and Terr. Sci., and Dep. of Geogr., Univ. of Waterloo, Ont., 1993.

Parkinson, C. L., and W. M. Washington, A large-scale numerical model of sea ice, *J. Geophys. Res.*, *84*, 311-337, 1979.

Pease, C. H., A model for the seasonal ablation and accretion of antarctic sea ice, *AIDJEX Bull. 29*, pp. 151-172, Div. of Mar. Resourc., Univ. of Wash., Seattle, 1975.

Peterson, J.T., and R.M. Rosson (Eds.), Summary report 1993, *Publ. 22*, 152 pp., Clim. Monit. and Diagnostics Lab., Environ. Res. Lab., NOAA, Boulder, Colo., 1994.

Reed, R. K., On estimating insolation over the ocean, *J. Phys. Oceanogr.*, *7*, 482-485, 1977.

Rossow, W. B., and R.A.Schiffer, ISCCP cloud data products, *Bull. Am. Meteorol. Soc.*, *72*(1), 2-20, 1991.

Schmetz, P., J. Schmetz, and E. Raschke, Estimation of daytime downward longwave radiation at the surface from satellite and grid point data, *Theor. Appl. Climatol.*, *37*, 136-149, 1986.

Schweiger, A. J, and J. R. Key, Arctic cloudiness: Comparison of ISCCP-C2 and Nimbus-7 satellite-derived cloud products with a surface-based cloud climatology, *J. Clim.*, *5*(12), 1514-1527, 1992.

Schweiger, A. J., and J. Key, Arctic Ocean radiative fluxes and cloud forcing estimated from the ISCCP C2 cloud data set, 1983-1990, *J. Appl. Meteorol.*, *33*, 948-963, 1994.

Semtner, A. J., A model for the thermodynamic growth of sea ice in numerical investigations of climate, *J. Phys. Oceanogr.*, *6*, 379-389, 1976.

Shine, K. P., Parameterization of shortwave flux over high albedo surfaces as a function of cloud thickness and surface albedo, *Q. J. R. Meteorol. Soc.*, *110*, 747-764, 1984.

Shine, K. P. and R. G. Crane, The sensitivity of a one-dimensional thermodynamic sea ice model to changes in cloudiness, *J. Geophys. Res.*, *89*, 10615-10622, 1984.

Shine, K. P. and A. Henderson-Sellers, The sensitivity of a thermodynamic sea ice model to changes in surface albedo parameterization, *J. Geophys. Res.*, *90*, 2243-2250, 1985.

Simpson, J. J., and A. Paulson, Mid-ocean observations of atmospheric radiation, *Q. J. R. Meteorol. Soc.*, *105*, 487-502, 1979.

Stephens, G.L., and P.J. Webster, Clouds and climate: Sensitivity of simple systems, *J. Atmos. Sci.*, *38*, 235-247, 1981.

Swinbank, W. C., Longwave radiation from clear skies, *Q. J. R. Meteorol. Soc.*, *89*, 339-348, 1963.

Tabata, S., Insolation in relation to cloud amount and sun's altitude, in *Studies on Oceanography*, pp. 202-210, Univ. of Wash. Press, Seattle, 1964.

Tsay, S.-C., and K. Jayaweera, Physical characteristics of Arctic stratus clouds, *J. Appl. Meteorol.*, *23*, 584-596, 1984.

Vowinckel, E., and S. Orvig, Insolation and absorbed solar at the ground in the Arctic, *Pub. in Meteorol. 53*, McGill Univ., Montreal, Que., 1962.

Zillman, J. W., A study of some aspects of the radiation and heat budgets of the southern hemisphere oceans, *Meteorol. Stud. Rep. 26*, Bur. of Meteorol., Dep. of the Inter., Canberra, A.C.T., 1972.

J.R. Key, Department of Geography, Boston University, 675 Commonwealth Avenue, Boston, MA 02215 (e-mail: jkey@bu.edu)

R.A. Silcox and R.S. Stone, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80303.

(Received March 31, 1995; revised October 26, 1995; accepted November 2, 1995.)