P4.5 INTERCOMPARISON AND VALIDATION OF SNOW AND SEA-ICE ALBEDO PARAMETERISATION SCHEMES IN CLIMATE MODELS

Pedersen, Christina A. * and Winther, Jan-Gunnar
Norwegian Polar Institute

ABSTRACT

In this study, seven GCM snow albedo schemes, two GCM sea-ice albedo schemes, a thermodynamic sea-ice model and a databased multiple linear regression model are intercompared and validated against a large amount of validation data. One site from Svalbard, one from the French Alps and six stations in the Former Soviet consisting of 59 years of point data are included for validating the snow albedo schemes. For the sea-ice counterpart, 14 years of data from North Pole Drifting Ice Stations were used as validation data.

For each of the available meteorological parameter from the different sites, a 95% confidence interval was constructed, and the significant meteorological parameters for modeling the snow and sea-ice albedo were identified. Based on the significant parameters, the multiple linear regression model was constructed to include the parameters: temperature, snow depth, positive degree day, dummy of snow depth and a constant for the snow albedo model, and temperature, snow depth, dummy of snow depth, cloud cover and a constant for the sea-ice albedo model. The overall goal of this work was not to determine a single "best" snow and sea-ice albedo parameterisation scheme, instead the characteristics of the various albedo schemes were investigated.

1 INTRODUCTION

Albedo is the ratio of reflected shortwave radiation to incoming shortwave radiation. Snow and sea-ice albedo are known to be crucial for heat exchange at high latitudes and high altitudes. In addition, the albedo is an important parameter in any regional or global climate model (GCM) because of its strong positive feedback properties. Even so, the way snow and sea-ice albedo are parameterised in GCM today are strongly simplified. During the last two decades, a substantial knowledge of the reflective characteristics of snow, glaciers, and sea ice have been gained, and a wide variety of field measurements [7]; [1]; [21]; [15] and theoretical studies [22]; [18] have been reported.

In this study eight snow and sea-ice albedo parameterisation schemes and a multiple linear regression model were intercompared and validated against *in situ* data from a variety of northern field sites. The simulations and results from the snow sites and snow albedo models are a summary of Pedersen and Winther (2004) [14]. The snow and sea-ice albedo models are presented in Section 2, while section 3 gives an overview of the data from the test sites. In Section 4, a multiple linear regression model is introduced. The main results and the discussion are presented in Section 5 and the conclusions in Section 6.

2 THE SNOW AND SEA-ICE ALBEDO MODELS

In this study the albedo parameterisation schemes were studied in an uncoupled system, and no feedback effects were considered. Also, the albedo schemes were validated against point measurements, not GCM grid cells.

Albedo parameterisations from seven GCM models and a one dimensional thermodynamic sea-ice model were included in this study. The models are described in Table 1. Only two of the GCM models have equations for sea-ice albedo. For the others, the models are either land surface schemes, or the sea-ice albedo is described as a constant.

The models can be divided into three categories depending on the model complexity. The simplest schemes are the temperature dependent schemes ECHAM5 [17] and UKMO [5]; [6], where both the snow and sea-ice albedo varies

*Corresponding author address: Christina A. Pedersen, Norwegian Polar Institute, N-9296 Tromsø, NORWAY; e-mail: christina@npolar.no

linearly with the temperature between an upper and lower limit. Above and below these limits the albedo is fixed.

The next category consisted of the four snow albedo models: ECMWF [9], CLASS [19], ISBA [3] and GISS [8]. The three first models have an iteratively albedo parameterisation scheme, *i.e*, the snow albedo value at a time step is dependent of the snow albedo value at the previous time step. All three models have different decay factors for melting and non-melting snow. The last model (GISS) includes an iteratively procedure for snow age, where the albedo is an exponential function of the snow age. All four models have the albedo value reset to its maximum value for new snowfall above a certain precipitation threshold.

The last category consisted of the more advanced model BATS [2] and the one dimensional thermodynamic sea-ice model by Ebert & Curry (1993) [4]. BATS includes different parameterisations for snow albedo for the visible and near-infrared bands, and for diffuse and direct radiation. The parameterisation include an iterative approach of the snow age. The snow cover fraction used in BATS is not the one originally included in the model, but the one introduced by Yang *et al.* (1997) [23]. The one dimensional thermodynamic sea-ice model developed by Ebert and Curry consists of albedo parameterisation for five different surfaces; dry snow, melting snow, bare sea-ice, melt pond and open water. Each of these surfaces are divided into four spectral band and a diffuse and direct fraction. The mean for each type is found from monthly varying weighting factors. The dry snow and open water surfaces are dependent on the solar zenith angle. The melting snow albedo is determined according to the snow depth, and are linearly reduced to the bare sea-ice albedo as the snow depth decreases. The bare sea-ice albedo is an nonlinear function of sea-ice depth, while the melt pond albedo is an exponential function of melt pond depth.

3 *IN SITU* VALIDATION DATA

In addition to intercompare the albedo models, the models were validated against *in situ* measurements. Data from Ny-Ålesund (Svalbard), Col de Porte (the French Alps) and six stations in the former Soviet Union (FSU) were chosen for validating the snow albedo schemes, while data from the drifting North Pole (NP) Stations in the Arctic Ocean was chosen for the sea-ice counterpart. These datasets are "point data", *i.e*, data collected at a point site. This is in contrast to the GCM models which have a large spatial resolution. Therefor, the assumption that the albedo and meteorological data are representative for the specified grid square have to be made.

Table 2 presents a summarize of the sites and the available meteorological parameters. The data from Ny-Ålesund at 78°55′N 11°56′E was collected during the years 1981-2002. The data from Col de Porte in the northern French Alps, located 1340 m above sea level at 45.3°N 5.8°E were collected during the years 1993-1996. The data from six soil stations from the former Soviet Union was collected for the period 1978-1983 [16]. The stations were part of the Hydrometeorological Service in the former Soviet Union described by Vinnikov and Yeserkepova (1991) [20] and include Khabarovsk at 48.5°N 135.2°E, Kostroma at 57.8°N 41.0°E, Ogurtsovo at 54.9°N 83.0°E, Tulun at 54.6°N 100.6°E, Uralsk at 51.3°N 51.4°E and Yershov at 51.4°N 48.3°E. Three drifting North Pole stations consisting of NP Station 19 from 1970-1972, NP station 22 from 1974-1981 and NP station 30 from 1988-1990 [11]. The data was obtained from the National Snow and Data Center (NSIDC).

4 MULTIPLE LINEAR REGRESSION ANALYSIS

In addition to the GCM snow and sea-ice albedo parameterisation schemes, the results from a multiple linear regression analysis on the data were included. The multiple linear regression model was build to include the meteorological parameters that were of real value in explaining the albedo. Thus, the significance of every available meteorological parameter was tested, by constructing the 95% confidence interval for each parameter coefficient [14]. If the parameter coefficient confidence interval includes zero, the coefficient is not significantly different from zero, and the corresponding meteorological parameter should be included in modeling the albedo. In addition to the observed meteorological parameters, positive accumulated degree days, *i.e*, a variable of accumulated positive temperatures since last snowfall, a dummy variable if it was snow on the ground and a constant were in-

Centre	Model/Reference	Snow Surface	Snow Cover Fraction	Sea Ice Surface	Sea Ice Fraction
Max Planck Institute for Meteorology	ECHAM5 Roechner *et al.* (2003) [17]	Linear function of T_s between -5°C and 0°C Fixed above at $\alpha_{min} = 0.3$ and below at $\alpha_{max} = 0.8$	Tanh function of S_n and slope terrain	Linear function of T_s between -1°C and 0°C Fixed above at $\alpha_{min} = 0.5$ and below at $\alpha_{max} = 0.75$ Not modified by snow cover	Fixed from monthly observations
Hadley Centre and UK Meteorological Office Forecast model	UKMO Essery *et al.* (2001, 1999) [5] [6]	Linear function of T_s between -2°C and 0°C Fixed above at $\alpha_{min} = 0.5$ and below at $\alpha_{max} = 0.8$	Exponential decay of S_n	Linear function of T_S between -5°C and 0°C Fixed above at $\alpha_{min} = 0.6$ and below at $\alpha_{max} = 0.85$ Modified by snow cover	AMIP monthly sea ice extent
European Centre for Medium-Range Weather Forecasts	ECMWF Web page (2003) [9]	Iteratively procedure Non-melt: constant decay Melt: exponential decay Reset to $\alpha_{max} = 0.85$ at large snowfall	Snow or bare ground	Fixed from monthly values	Surface analysis
Canadian Land Surface Scheme	CLASS Verseghy (1991) [19]	Iteratively procedure Different exponential decay for T_S above and below 0°C Reset to $\alpha_{max} = 0.84$ at large snowfalls	Snow or bare ground		
Météo-France Climate Model ARPEGE	ISBA Land-Surface Scheme Douville *et al.* (1995) [3]	Iteratively procedure Cold snow: constant decay Melting snow: exponential decay Reset to $\alpha_{max} = 0.85$ at large snowfalls	Non-linear function of S_n		
Goddard Institute for Space Studies	GISS Hansen *et al.* (1983) [8]	Exponential decay of snow age Snow age is an iterative function, exponential dependent of new snow fall $\alpha_{max} = 0.85$	Exponential decay of S_n	Model I: constant value	Fixed from data
National Center for Atmospheric Research	BATS Bonan *et al.* (2002) [2]	Linear dependency of snow age and θ_0 Snow age is a function of change in S_n	Tanh function of d_s (this approach is suggested by [23])		
	1D thermodyn. sea-ice model Ebert & Curry (1993) [4]	Dry snow: f(μ_0) Melting snow: f(d_s, d_i) Linear interpolation between melting snow and sea-ice	Linear function of d_s	Sea ice: f(d_i) Melt pond: f(d_p)	The surface type must be specified

Table 1: Existing albedo schemes/parameterisations included in the comparison. T_S is the surface temperature, and θ_0 the sun zenith angle, $\mu_0 = \cos(\theta_0)$. S_n and d_s are snow depths, given in SWE and m respectively. d_i and d_p are the sea-ice thickness and melt pond depth, respectively.

cluded.

It is crucial to test the multiple linear regression model on data that were not included in the building of the model [13]. If not, the error between the predicted and observed values will certainly be underestimated. To evaluate the predicting quality of the linear regression model, the available data were divided into two sets, a "training set" and a "test set". All of the data except from one year were used to build the model (training set), and the last year was used to test the predictive properties of the model (test set).

4.1 Building the Multiple Linear Regression Models (MLRM)

To build the multiple linear regression model the following parameters were tested: constant, temperature, cloud cover, corrected precipitation, wind speed, snow depth, positive degree day and dummy snow depth for the snow albedo model, and constant, air temperature, cloud cover, corrected precipitation, wind speed, snow depth, positive degree day, dummy snow fall and dummy snow depth for the sea-ice albedo model.

The meteorological parameter coefficients were calculated from ridge regression, and the 95% one-at-a-time confidence intervals were calculated for each coefficient. The constant, temperature, positive degree day and dummy snow depth were significantly different from zero for all snow sites, while the snow depth was significantly different for all but one, so these parameters should be included in the snow albedo model. The constant, temperature and snow depth were significant different from zero for all the NP Station, while the dummy snow depth was significantly different for all but one and the cloud cover was significantly different from zero for NP Station 22. Since the years of available data for the NP Station differs substantially, we have chosen to include the dummy snow depth and cloud cover in the sea-ice albedo model since they were significant for the NP Sta-

Parameter	Ny-Ålesund	Col de Porte	FSU Stations	NP Stations
Surface Albedo	Yes	Yes	Yes	Yes
Air/Surface Temp.	Yes/No	Yes/No	Yes/Yes	Yes/No
Max/Min Temp.	Yes	No	No	No
Wind Speed	Yes	Yes	Yes	Yes
Precipitation	Yes(R)	Yes(C)	Yes(R)	Yes(R)
Precip. Type	No	Yes	No	Yes
Cloud Cover Fr.	Yes	Yes	Yes	Yes
Snow Depth	Calc.	Yes	Calc.	Yes

Table 2: The available meteorological parameters from the different sites. C means corrected measurement, while R is raw data. Calc. is used when the snow depth is estimated from the hydrological model HBV [12] instead of measured directly.

Site	Const	Temp	SnowD	DegDay	DSnowD
Ny-Ålesund	0.20	-0.04	0.03	-0.04	0.55
Col de Porte	0.24	-0.06	0.01	-0.06	0.45
Khabarovsk	0.26	-0.06	0.05	-0.03	0.18
Kostroma	0.29	-0.02	0.09	-0.03	0.19
Ogurtsovo	0.22	-0.05	0.06	-0.04	0.25
Tulun	0.30	-0.05	0.11	-0.02	0.12
Uralsk	0.20	-0.03	0.03	-0.04	0.38
Yershov	0.21	-0.04	0.05	-0.04	0.26
Mean snow	0.24	-0.04	0.05	-0.04	0.30
	Const	Temp	SnowD	CloudC	DSnowD
NP Station 19	0.69	-0.03	0.03	0.01	0.11
NP Station 22	0.69	-0.04	0.05	0.02	0.07
NP Station 30	0.75	-0.02	0.04	0.02	0.04
Mean sea-ice	0.71	-0.03	0.04	0.02	0.07

Table 3: The significant meteorological parameters and regressors coefficients in the multiple linear regression problem at a $\alpha = 0.05$ significants level. The solution was found by ridge regression. The abbreviation used are the following: Const = constant, Temp = temperature, CloudC = cloud cover, Prec = corrected precipitation, WindS = wind speed, SnowD = snow depth, DegDay = positive degree day, DSnowF = dummy snow fall and DSnowD = dummy snow depth. The upper table is for the snow albedo model (table from Pedersen and Winther (2004) [14]), while the lower table is for the sea-ice albedo model.

tion 22 which consisted of 8 years of data, compared to the other two stations 2 years of data. The significant meteorological parameters and their respective coefficients are summarized in Table 3.

5 RESULTS AND DISCUSSION

5.1 Snow albedo models

The observed snow albedo from Ny-Ålesund and Col de Porte attained very high values, often above 0.95 (Ny-Ålesund) or 0.90 (Col de Porte) for new snow fall, which was well above what was simulated by the snow albedo schemes. The maximum albedo threshold for any model was $\alpha_{max} = 0.85$. For the six FSU sites the albedo values were substantially lower, and closer to the modeled values. Almost all the models underestimated the high winter albedo, and this was especially predominant for Ny-Ålesund with its very high cold winter snow albedo values. The modeled snow albedo also varied more than the observed albedo. This was especially true for Ny-Ålesund and Col de Porte, where the observed snow albedo stayed relatively higher through the cold winter season compared to the modeled albedo. The modeled snow albedo decreased at a faster rate or by a larger magnitude during the winter snow metamorphosis than the observed albedo.

In the melting season the modeled snow albedo was very dependent on the snow cover fraction, which again was determined almost entirely by the snow depth. For Col de Porte, where the snow depth was measured, all the models responded accurately by decreasing the snow albedo at a correct rate and time. For the other sites, where the snow depth was estimated from the HBV model, the results were somewhat less satisfying. For Ny-Ålesund, the models were just as often melting away the snow cover and decreasing the albedo too early in the season as too late, while for all the FSU stations the modeled snow albedo was decreased too late. During the summer all models were fixed to the same ground albedo (0.2), except the MLRM. The MLRM was most varying, but it seemed to underestimate the high peaks and overestimate the low peaks. This was because the model, by definition, tried to minimize the error, *i.e*, many small errors are more tolerated than few large.

The temperature dependent schemes (ECHAM and UKMO) showed a weakness by fixing the albedo to the minimum value as soon as the temperature was equal to or above freezing. At a temperate site like Col de Porte where the temperature reached 0° several times during the winter, this feature became predominant. This was seen for both the temperature dependent models, but was most clearly seen for ECHAM5 since its minimum was at $\alpha_{min} = 0.3$ against UKMOs at $\alpha_{min} = 0.5$. Also in the melting season these two schemes seemed to reach the minimum value too early. The iterative snow albedo schemes had the albedo decreasing exponentially depending on the temperature when the snow aged. When the snow albedo was at its minimum value, it was fixed until a new snow fall above a certain precipitation threshold fell. In a low precipitation site like Ny-Ålesund, a new snow fall above the specified precipitation threshold rarely happened, and therefore the albedo was wrongly fixed at its minimum value. This occurred for all the iterative schemes, but was predominant for ISBA because of its large precipitation threshold. The new snowfall threshold (precipitation threshold) varied widely among the models between 2-10 mm SWE. In addition, the precipitation measurements were connected with large uncertainties, and therefore the determination of the threshold value caused large errors.

5.2 Sea-Ice albedo models

Also for the sea-ice albedo schemes the modeled sea-ice albedo were underestimated during the cold winter season, because the maximum albedo specified by each model were fixed. For stable cold winter conditions, the thermodynamic sea-ice model had the highest value varying from January/February at 0.81, March at 0.80 and April/May at 0.79 (dry snow values with solar zenith angle at 0°). During cold winter conditions all the three sea-ice albedo schemes were relative constant at their maximum values, while the observed albedo was more varying. This is in contrast to the snow albedo schemes described above.

Often the drop in albedo due to melting was initiated too early for the sea-ice albedo models. Both the modeled albedo from ECHAM5 and UKMO dropped to their lower value at 0.5 (minimum sea-ice albedo for ECHAM5 and minimum snow albedo for UKMO), which often was often too low compared with the observed albedo in the early melt season. However, the observed albedo dropped below this value during summer, but none of the models were able to follow because they were fixed at their minimum albedo value at $\alpha_{min} = 0.5$. The thermodynamic sea-ice model have separate equations for melt pond albedo and open water albedo and are certainly capable of modeling the albedo during summer period more accurately, but unfortunately, the validation data did not include information on melt-pond and melt-pond fraction or open water fraction, and therefor these equations had to be left out.

The temperature dependent sea-ice albedo schemes (ECHAM and UKMO) showed the same weakness as the temperature depended snow albedo schemes, by fixing the albedo to its minimum value as soon as the temperature increased above 0°C. With ECHAM5 sea-ice albedo varying between 0.75 and 0.5 when the temperature varies between $[-2, 0]$°C, and UKMO varying between 0.85 and 0.6 for temperatures between $[-5, 0]$°C, the modeled albedo was fixed to its maximum and minimum values too often.

The thermodynamic model show advantages over the other models, at least in theory, by describing five surface types, and parameterise the albedo different for each surface type: dry snow, melting snow, bare sea-ice, melt pond and open water (each depending on the parameters given in Table 1).

5.3 Quantitatively describing the model performances

The two well-known error measurements root mean square error (RMSE) and correlation coefficient (ρ) were evaluated and compared for every model and site. Both measures were considered, because they reflect different features of the models. The RMSE measures the "closeness" between the model and the observations, and therefore an offset will be highly punished. ρ measures the linear co-variance, *i.e*, if the observations are increasing/decreasing, then so should the model curve, and it is not concerned about the offset. Together these two measurements describe the goodness of the fit.

In Table 4 the RMSE and the ρ are given for all the snow albedo models and -sites averaged over the years. In addition the mean RMSE and mean ρ are given. The lowest RMSE (0.08) was observed for ECHAM5, UKMO, ISBA, GISS and MLRM for various sites. The model with the smallest mean RMSE for all sites was MLRM. It was a clear difference between the models performance among the different sites. The models were doing worst in predicting the albedo in Ny-Ålesund, while the model performance was best overall for the FSU sites. The models with the highest ρ were UKMO and BATS. ρ was lowest with 0.56 for ECHAM5 model in Col de Porte, and overall the mean ρ was lowest for Col de Porte. The model with the highest mean ρ is UKMO.

Table 5 shows the corresponding RSME and ρ for the sea-ice models and -sites. In addition the mean RMSE and mean ρ are given. The highest RSME was found for ECHAM5 (0.15) at NP Station 30, while the lowest was found for MLRM (0.09) at NP Station 19. The model with the smallest mean RMSE for all sites was MLRM. The models performance did not change very much between the sites. The model with the highest ρ were the thermodynamic sea-ice model for NP station 19, while UKMO and the thermodynamic sea-ice model had lowest ρ for NP station 30.

6 CONCLUSIONS

In this work the snow and sea-ice albedo parameterisation schemes of seven GCMs, a thermodynamic sea-ice model and a multiple linear regression model have been compared with each other and with a large amount of *in situ* validation data. Eleven sites covering the northern hemisphere (Svalbard, the French Alps, six stations in the former Soviet Union and three drifting ice stations in the Arctic Ocean) consisting of 73 years of data were used as validation data.

Almost all the snow albedo schemes underestimated the high winter albedo observations, and also the modeled albedo varied more than the observed albedo. The modeled snow albedo decreased at a faster rate or by a larger magnitude during the winter snow metamorphosis than the observed albedo. The eight snow albedo schemes showed large dissipation in their behavior. The category of temperature dependent schemes showed a too large sensitivity to temperature. That is, as soon as the temperature exceeded freezing temperature, the snow albedo was set to its minimum value. Another drawback was connected to the iterative albedo schemes, and the resetting to maximum snow albedo value after a new snowfall. The new snowfall threshold (precipitation threshold) was an important parameter, but it varied widely among the models. In addition the precipitation measurements were connected with large uncertainties. Most of the models estimated the snow cover fraction, and the surface albedo was a weighted mean between the snow albedo and the bare ground albedo. An underestimated snow cover fraction led to an underestimated surface albedo, and vice versa.

The three sea-ice albedo models showed more similar behavior. The modeled sea-ice albedo was usually underestimated. During the cold winter period the sea-ice models were relative constant at their maximum values, while the observed albedo was more varying and at higher values. The modeled sea-ice albedo was decreasing too fast in the spring melting, and the minimum albedo value was often too low compared with the observed albedo. In summer the observed sea-ice albedo dropped below this value, but none of the models were able to follow it. The temperature dependent sea-ice albedo models (ECHAM and UKMO) showed the same weakness as the temperature depended snow albedo schemes.

Due attention was made towards the multiple linear regression model. The 95% confidence interval was constructed for each of the available meteorological parameter (including some additionally made parameters). From the con-

	ECHAM5	UKMO	ISBA	GISS	CLASS	ECMWF	BATS	MLRM	Mean
Ny-Ålesund	0.24 (0.82)	0.16 (0.91)	0.22 (0.87)	0.20 (0.88)	0.14 (0.92)	0.14 (0.92)	0.16 (0.89)	0.12 (0.93)	0.17 (0.89)
Col de Porte	0.31 (0.56)	0.14 (0.76)	0.13 (0.77)	0.12 (0.85)	0.09 (0.89)	0.11 (0.86)	0.15 (0.85)	0.09 (0.88)	0.14 (0.80)
Khabarovsk	0.11 (0.89)	0.14 (0.87)	0.11 (0.84)	0.10 (0.88)	0.15 (0.83)	0.17 (0.79)	0.16 (0.86)	0.11 (0.84)	0.13 (0.85)
Kostroma	0.09 (0.89)	0.08 (0.93)	0.08 (0.91)	0.08 (0.91)	0.10 (0.90)	0.11 (0.90)	0.10 (0.94)	0.08 (0.91)	0.09 (0.91)
Ogurtsovo	0.09 (0.93)	0.12 (0.91)	0.12 (0.83)	0.11 (0.87)	0.13 (0.87)	0.14 (0.87)	0.14 (0.87)	0.12 (0.86)	0.12 (0.88)
Tulun	0.08 (0.93)	0.10 (0.92)	0.13 (0.87)	0.11 (0.89)	0.12 (0.86)	0.14 (0.82)	0.10 (0.92)	0.10 (0.89)	0.11 (0.88)
Uralsk	0.09 (0.93)	0.08 (0.95)	0.12 (0.87)	0.11 (0.89)	0.11 (0.91)	0.11 (0.91)	0.10 (0.93)	0.10 (0.90)	0.10 (0.91)
Yershov	0.08 (0.92)	0.10 (0.92)	0.11 (0.85)	0.11 (0.88)	0.13 (0.87)	0.14 (0.87)	0.14 (0.88)	0.11 (0.87)	0.12 (0.88)
Mean	0.14 (0.86)	0.12 (0.90)	0.13 (0.85)	0.12 (0.88)	0.12 (0.88)	0.13 (0.87)	0.13 (0.89)	0.10 (0.89)	

Table 4: Total RMSE and ρ (in brackets) between the observed and modeled albedo. All seven GCM snow albedo parameterisation schemes and the data-based MLRM are included. In addition the mean RMSE and mean ρ are given. The table is from Pedersen and Winther (2004) [14].

fidence intervals the significant meteorological parameters for modeling the snow and sea-ice albedo were identified separately. Based on the significant meteorological parameters, the multiple linear regression model for snow included: temperature, snow depth, positive degree day, dummy of snow depth and constant, and the multiple linear regression model for sea-ice included: temperature, snow depth, cloud cover, dummy of snow depth and constant. To put this in a broader perspective, this means that when building a snow or sea-ice albedo model (whether it is in GCMs or elsewhere), the model should include these meteorological parameters.

The overall goal of this work was not to determine a single "best" snow and sea-ice albedo parameterisation scheme, instead the characteristics of the various albedo schemes were investigated. But, we felt that the iterative snow albedo schemes were superior to the temperature dependent schemes. However, the new snowfall threshold introduced in the iterative schemes needs to be more carefully examined. Also the parameterisation of snow cover fraction should be handled with care, and further investigated. The thermodynamic sea-ice model showed advantages over the other models by describing five surface types, and parameterise the albedo different for each type. Dry snow, melting snow, bare sea-ice, melt pond and open water are defined as separate surfaces, each depending on the parameters as given in Table 1.

More work remains to be done on both snow and sea-ice albedo parameterisation. The intercomparison needs to be considered on a larger spatial scale, *i.e.* GCM grids of typically 1° size. Other factors will then become predominant in the investigation, for example the snow cover- and sea-ice fraction will be of special interest, and must be defined at a GCM grid. *In situ* ground validation data could be replaced with remote sensing validation data. For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) snow albedo product [10] is currently available, and could be a valuable data source in this context. At the moment no MODIS sea-ice albedo product exists. Also the spectral dependency of the albedo should be included to improve the albedo parameterisations further.

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	ECHAM5	UKMO	1D sea-ice model	MLRM	Mean
NP Station 19	0.14 (0.62)	0.10 (0.61)	0.11 (0.67)	0.09 (0.60)	0.11 (0.63)
NP Station 22	0.13 (0.62)	0.11 (0.62)	0.13 (0.57)	0.12 (0.57)	0.12 (0.60)
NP Station 30	0.15 (0.44)	0.12 (0.40)	0.13 (0.40)	0.10 (0.41)	0.13 (0.41)
Mean	0.14 (0.56)	0.11 (0.54)	0.12 (0.55)	0.10 (0.53)	

Table 5: Total RMSE and ρ (in brackets) between the observed and modeled albedo. The two GCM sea-ice albedo parameterisation schemes, the thermodynamic sea-ice model and the data-based MLRM are included. In addition the mean RMSE and mean ρ are given.

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