Chinese Journal of Polar Science, Vol. 19, No. 2, 108 – 122, December 2008

Snow and sea ice thermodynamics in the Arctic: Model validation and sensitivity study against SHEBA data

Cheng Bin[1,4], Timo Vihma[1,4], Zhang Zhanhai[3], Li Zhijun[4] and Wu Huiding[3]

1 Finnish Institute of Marine Research (FIMR), P. O. Box 33, FI-00931, Helsinki, Finland

2 Finnish Meteorological Institute, P. O. Box 503, FI-00101, Helsinki, Finland

3 State Oceanic Administration Key Laboratory for Polar Science, Polar Research Institute of China, Shanghai 200136, China

4 State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China

Received September 20, 2008

Abstract Evolution of the Arctic sea ice and its snow cover during the SHEBA year were simulated by applying a high-resolution thermodynamic snow/ice model (HIGHTSI). Attention was paid to the impact of albedo on snow and sea ice mass balance, effect of snow on total ice mass balance, and the model vertical resolution. The SHEBA annual simulation was made applying the best possible external forcing data set created by the Sea Ice Model Intercomparison Project. The HIGHTSI control run reasonably reproduced the observed snow and ice thickness. A number of albedo schemes were incorporated into HIGHTSI to study the feedback processes between the albedo and snow and ice thickness. The snow thickness turned out to be an essential variable in the albedo parameterization. Albedo schemes dependent on the surface temperature were liable to excessive positive feedback effects generated by errors in the modelled surface temperature. The superimposed ice formation should be taken into account for the annual Arctic sea ice mass balance.

Key words Arctic, sea ice, Model validation and sensitivity study, SHEBA data.

1 Introduction

By regulating the exchange of heat, moisture, and momentum between the ocean and atmosphere, thermodynamics of sea ice and its snow cover play an important role in the Arctic climate system. Modelling studies of snow and sea ice thermodynamics have been carried out for a few decades, but unsolved problems still remain. During a freezing season, the sea ice mass balance is relatively easy to be modelled well. A simple analytical model, such as the Stefan's law, may give a good first-order estimate for the ice growth. During the ice thermal equilibrium and melting seasons, however, an accurate modelling of ice mass balance may require a better understanding of the surface albedo feedback mechanism, effect of absorbed solar radiation on sub-surface snow/ice melting, snow-to-ice transformation, and a good simulation of the temperature profile in snow and ice.

Particular challenges remain in the parameterization of surface albedo and the radiative energy absorbed and distributed within the snow and ice cover, as well as in modelling the contribution of snow to sea ice energy and mass balance. It has been found out that the simulation of the Arctic sea ice responds most sensitively to the parameterization of the sea-ice albedo[1]. Sea ice is involved in key climate feedbacks (ice-albedo feedback, cloud-radiation feedback). For example, snowfall largely increases the surface albedo, reflecting a larger portion of the incoming solar radiation and reinforcing the cooling of the atmosphere, providing a strong support to the maintenance of ice cover. On the other hand, melting of snow and ice will reduce the surface albedo favoring further melting. This positive ice-albedo feedback has a significant impact on climate change in polar-regions[2-4]. The effect of surface albedo during the melt season is often poorly quantified mainly due to our inability to accurately know the surface characteristics such as snow depth and melt pond fraction. This was reflected in the results of Sea Ice Model Inter-comparison Project Part 2 (SIMIP2), i. e., during the winter season, various models yielded approximately similar ice growth, while during the summer season melting of snow and ice were modelled differently[5]. The onset of ice melt is mainly controlled by the time of disappearance of the overlying snow cover. Since the classical sea ice thermodynamic model of Maykut and Untersteiner, models have been further developed by, among others, Ebert and Curry, Launiainen and Cheng, Bitz and Lipscomb, Liston *et al.*, and Huwald *et al.* (2005a)[6]. The High-Resolution Sea Ice Thermodynamic Model (HIGHTSI) was developed in the Finnish Institute of Marine Research (FIMR) as a long-term Sino-Finnish collaboration. In the latest model application[7], the main focus was to investigate the impact of external forcing, snow physics, and the model resolution on snow and ice mass balance by carrying out a number of numerical experiments in synoptic (10 days in early autumn during the CHINARE-03 ice camp) and seasonal (May-September) scales. However, due to lack of seasonal validation data, various model experiments could only be compared against each other.

The most extensive year-round data set on the Arctic snow and ice thermodynamics and their forcing factors originates from the project Surface Heat Budget of the Arctic Ocean (SHEBA, Uttal *et al.*, 2002)[8] in 1997-1998. The SHEBA data sets have been used to validate surface albedo schemes and parameterization of melt ponds[9]. The impact of forcing data on sea ice simulation was also investigated using SHEBA data sets [10,11]. Huwald *et al.* (2005a)[6] modelled the SHEBA year applying a multi-layer sigma-coordinate thermodynamic sea ice model. The results indicated that ice thickness is very sensitive to the oceanic heat flux. In this study, we apply HIGHTSI to simulate the SHEBA year. We pay detailed attention to the effect of albedo on snow and ice mass balance, and carry out sensitivity tests to investigate the importance of model vertical resolution as well as the role of snow to ice transformation. The HIGHTSI model is briefly introduced and various albedo schemes are presented in Section 2. The results are presented and interpreted in Section 3, and the final conclusions are drawn in Section 4.

2 Thermodynamicc sea ice model and albedo schemes

The HIGHTSI model is targeted for process studies, i. e. , to simulate the evolution of snow/ice surface temperature, in-snow/ice temperature, and snow/ice thickness. Special attention is paid to the parameterization turbulent heat fluxes with the atmospheric boundary layer (ABL) stratification taken into account. The penetrating global radiation through the surface is parameterized, making the model capable to quantitatively calculate sub-surface melting. The model has been validated against field data and successfully applied to the Bohai Sea, Baltic Sea[12-14], central Arctic, and the Antarctic[7]. The validation studies have yielded good results for the surface heat balance, snow/ice mass balance, and snow/ice temperature regimes. It has been found out that a successful simulation of temperature regimes within snow/ice during a melting season with large solar radiation requires a high vertical resolution[16]. Recent developments of HIGHTSI have also included attentiosuperimposed ice formation (ice refrozen from melt water)[14] and sensitivity to precipitation forcing[7].

Many parameterizations of the snow and sea ice albedo have been developed. Most of the schemes are based on measurements carried out in the Arctic. In this study, we carry out model sensitivity studies in terms of various albedo schemes. The albedo schemes applied are listed in Table 1. We group these parameterizations into four categories (I, II, III and IV) ranging from simple to sophisticated. A single broadband value as a function of the surface status (e. g. snow, ice, wet snow, and wet ice) is defined as the simplest albedo scheme normally applied in large-scale sea ice climate models. The next category of schemes refers to surface temperature (Tsfc) dependent albedo, i. e. , the surface status is quantitatively taken into account. Some regional climate models (e. g. HIRHAM, ECHAM5, and HadCM3) favour such albedo schemes. In addition to Tsfc, more complexity can be included in albedo parameterizations by introducing the time development of snow and ice thickness, as well as empirical threshold values of them determined from field observations. These threshold values are used to define the albedo function. Albedo schemes in this category[17,18] are applicable for sea ice climate and process models. Pirazzini *et al.* (2006)[19] investigated albedo changes during a snow-melt season in the Baltic Sea and made an adaptation of the Flato and Brown (1996)[18] scheme to be more suitable for the Baltic Sea ice modelling. The most sophisticated albedo scheme is in our last category, i. e. albedo is parameterized according to temperature, snow and ice thickness as well as the spectral dependence, solar zenith angle, and atmospheric properties[20].

On the basis of SHEBA observations, a standard forcing data set has been created in SIMIP2. It was particularly designed for comparison of sea ice thermodynamic models. Figure 1 shows those in situ measurements. The in situ snow depth measurements show significant spatial and temporal variations. The SIMIP2 concludes[11]: "the prescribed snowfall ates produce snow accumulation that is considerably less than observed. This may be a consequence of gauge under catch or local in-homogeneity in accumulation. Therefore, in order to be more faithfully to reproduce local conditions at the test site, the snowfall rate was manually increased by 50%, i. e. the observed snow fall rate was multiplied by 1.5".

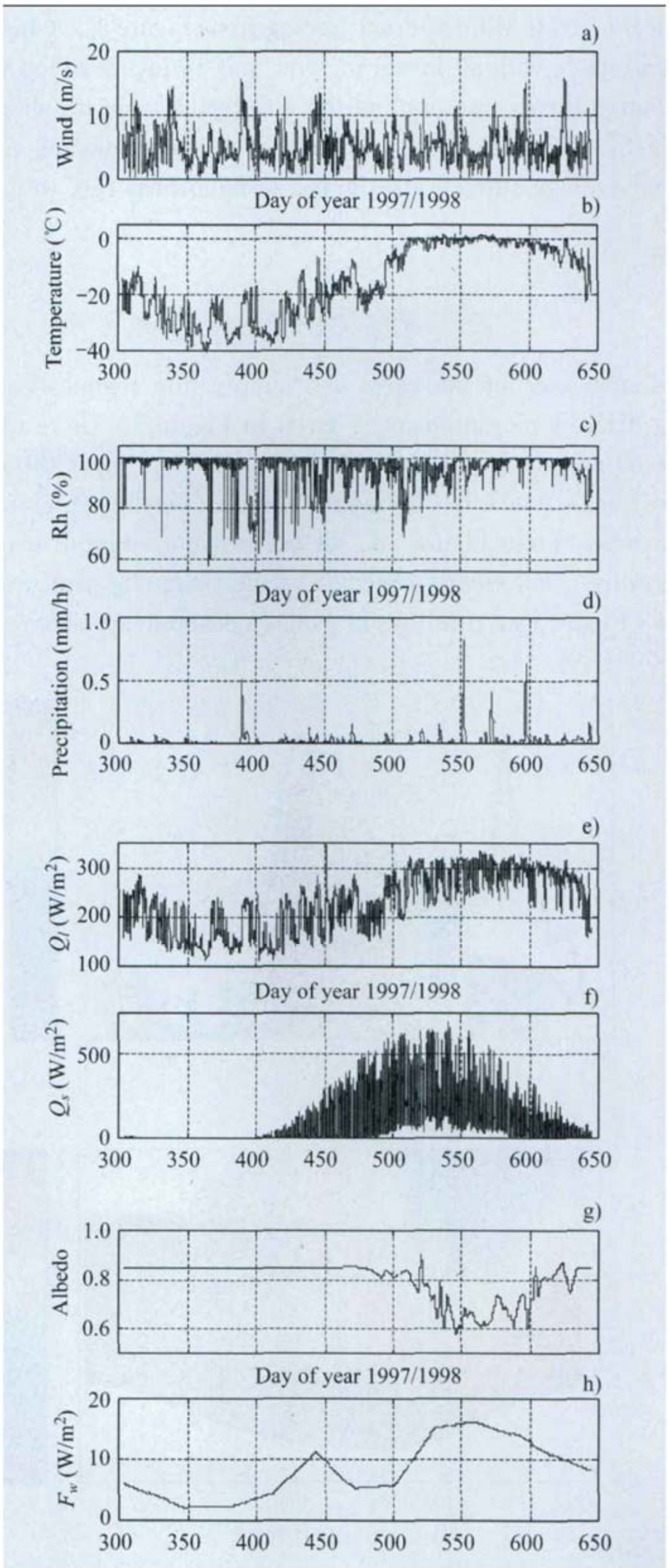

Fig. 1 The SHEBA observations used as external forcing data for the Sea Ice Thermodynamic Model Inter-comparison Project (SIMIP2). Rh is relative humidity, Ql is the downward longwave radiation, Qs is the shortwave radiation and Fw is the oceanic heat flux.

A control run was made with external forcing from Figure 1. A high vertical resolution in a Lagrangian grid mode with 30 layers in snow and 30 layers in ice was used. Instead of parameterized radiative fluxes, we applied the observed downward shortwave and longwave radiation in HIGHTSI. This eliminates the impact of cloudiness on the surface heat balance. The observed average surface albedo and oceanic heat flux were also applied in the control run.

3 Results

The modelled snow and ice thickness and temperature regimes are given in Figure 2. The corresponding SHEBA measurement is given in Figure 3. There was a large difference between the observed and modelled snow thickness between days 300 and 400. The measurement was solely from Gauge 69. The large difference maybe explained by the local variability of snow thickness. From Figure 1d, we see a major snowfall event around day 380. This event was, however, not clearly reflected in the Gauge 69 measurement, probably due to the strong wind (Figure 1a) resulting in gauge measurement errors. On the other hand,

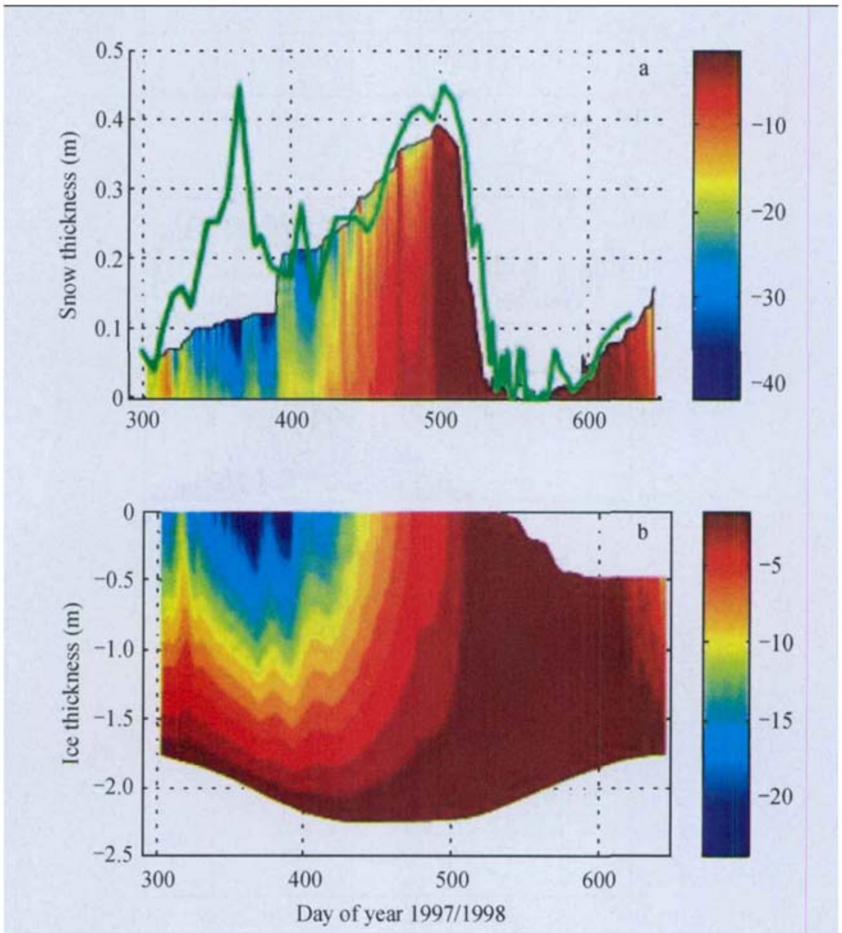

Fig. 2 (a) The HIGHTSI modelled snow thickness and temperature (°C) field and observed snow thickness (green line) at a single location (Gauge No. 69) during the SHEBA year. (b) HIGHTSI modelled ice mass balance and temperature during SHEBA year.

the strong local snow accumulation at Gauge 69 from day 300 to 360 was not detectable from the spatial average gauge-based accumulation (Figure 4 in Huwald *et al.* 2005a[11]). The main factors that affect modelled snow thickness are the precipitation and snow melt. In HIGHTSI, the precipitation was an external forcing, while snowmelt was a prognostic variable. After day 400, the modelled snow thickness showed reasonable agreement with the in situ measurement indicating that the HIGHTSI well reproduced the snowmelt.

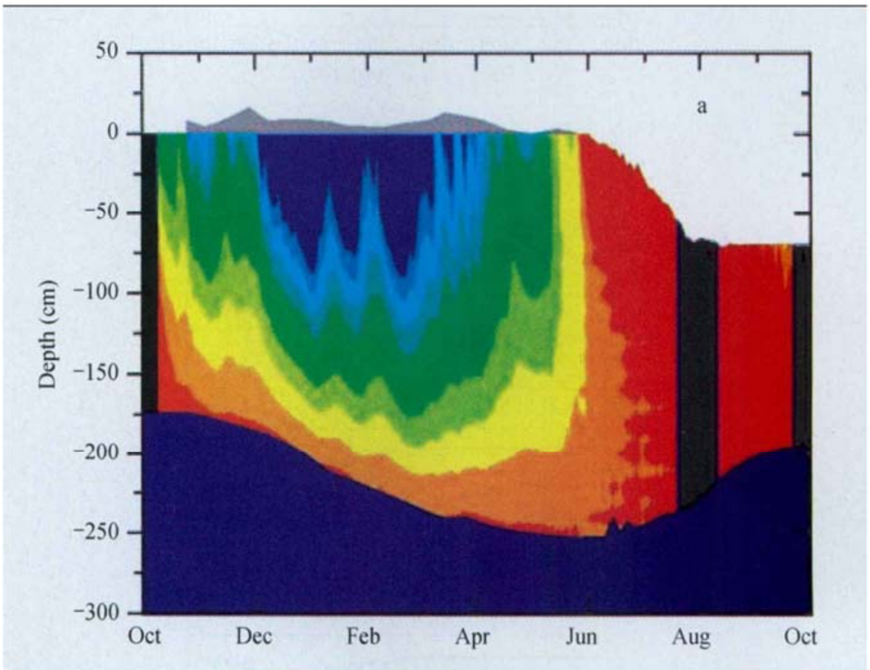

Fig. 3 Observed ice thickness and temperature regime during SHEBA. The internal ice temperature is displayed using color contours, with cold (−20°C) as blue and warm (0°C) as red. The gray shaded area represents snow depth, and the black, missing data. The boundary between red and navy blue denotes the ice-ocean interface (Figure from Perovich *et al.* 2003[21]).

The ice thickness was modelled reasonable well, in particular the bottom mass balance. This is because we applied the observed oceanic heat flux to minimize the uncertainties originating from the ocean. The surface ice melting was underestimated compared with the measurement (Figure 3), because the surface albedo of the control run was prescribed based on the average of observations, which were not made over melt ponds. The surface ice melting may increase some 10 ~ 15%, if the albedo of melt ponds is considered.

The control run yielded good results by utilizing the maximum amount of observations as external forcing. The precipitation was particularly important for a good snow thickness simulation. Once the snow precipitation was specified, a proper modelling of the seasonal evolution of the snow and ice strongly depends on the surface albedo.

To understand the impact of surface albedo on seasonal snow and ice mass balance, we carried out a number of model runs with various albedo parameterization schemes. The model forcing is still from Figure 1, except the surface albedo was parameterized (Table 1).

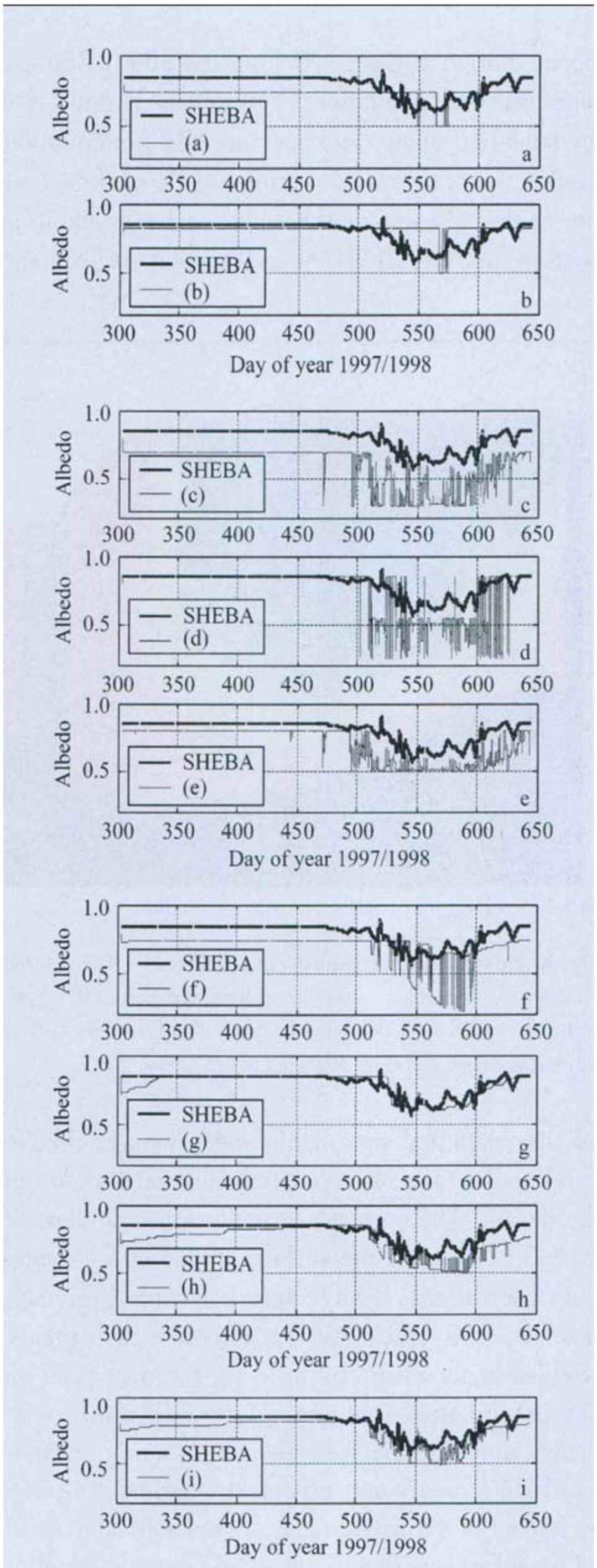

Fig. 4 The HIGHTSI calculated albedo (thin line) versus the SHEBA measurements (thick line). Various albedo schemes were incorporated into the HIGHTSI (See Table 1 for formulae).

Table 1. Various snow and sea ice albedo schemes applied in this study

Albedo category		Albedo parameterization	Applications of albedo schemes
C_I	(a)	$\alpha = 0.75$(snow); $\alpha = 0.5$(ice) Parkinson & Washington (1979)	Large scale climate model
	(b)	$\alpha = 0.8$(dry snow), 0.77(wet snow); $\alpha = 0.57$(dry ice), 0.51(wet ice) Perovich (1996)	Climate/process models
C_{II}	(c)	$\alpha = \alpha_{max} - \exp(-0.5(T_{melt} - T_{sfc})((\alpha_{max} - \alpha_{min})$ $\alpha_{max} = 0.7; \alpha_{min} = 0.3$ Liu *et al.* (2007)	Regional climate model (HIRLAM)
	(d)	$\alpha = 0.85, T_{sfc} \leqslant -3°C; \alpha = 0.55 - 0.133(T_{melt} - T_{sfc}), T_{sfc} > -3°C$ Køltzow *et al.* (2003)	Regional climate model (REMO)
	(e)	$\alpha = 0.8, T_{sfc} \leqslant -10°C; \alpha = 0.8 - 0.03(T_{sfc} + 10), -10°C < T_{sfc} \leqslant 0°C$; $\alpha = 0.5, T_{sfc} > 0$ Liu. J personal communication	Regional climate model (HadCM3)
C_{III}	(f)	$\alpha_i = \max(\alpha_o, c_{11}(H_i)^{0.28} + 0.08, \alpha = 0.75, T_{sfc} < T_{melt}$ $c_{10} = 0.1, c_{11} = 0.44,$ $\alpha_i = \min(\alpha_{mi}, c_{12}(H_i)^2 + \alpha_o), \alpha_s = 0.65, T_{sfc} = T_{melt}$ $c_{12} = 0.075, \alpha_{mi} = 0.55,$ $\alpha = \alpha_o \quad H_i < H_{min} \quad \alpha_o = 0.15, H_{min} = 0.001$ m. $\alpha = \max(\alpha_s, \alpha_i + H_s \times (\alpha_s - \alpha_i)/c_{10}), \quad H_i \geqslant H_{min}, H_s \leqslant c_{10}$ $\alpha = \alpha_s \quad H_i \geqslant H_{min}, H_s > c_{10}$ Flato and Brown (1996)	Sea ice process studies and climate models
	(g)	$\alpha_i = \min(\alpha_{mi}, c_{12} \times (H_i)^{1.5} + 0.15), \alpha_s = 0.8, \quad c_{10} = 0.1, c_{12} = 0.85$ $\alpha = \min[\alpha_s, \alpha_i + H_s \times (\alpha_s - \alpha_i)/c_{10}] \quad H_i \geqslant H_{min}, H_s > c_{10} \quad \alpha_{mi} = 0.55,$ $\alpha = \alpha_s \quad H_i \geqslant H_{min}, H_s > c_{10}$ Pirazzini *et al.* (2006)	Process studies for snowmelt season in the Baltic Sea
	(h)	$\alpha_{it} = \alpha_o + \alpha_i(1 + tanh(H_i - 0.2)/0.8))/2 - 0.1(1 + tanh((\min(T_{sfc} - T_{melt}, T_{melt}) + 1.2)/0.03))/2$ $\alpha_{st} = \alpha_s - 0.1(1 + tanh((T_{sfc} + 1.2)/0.03))/2$ $\alpha_o = 0.1; \alpha_i = 0.5; \alpha_s = 0.9$ $\alpha = \alpha_{it}$, if $H_s < 0.01m; \alpha = \alpha_{it} + H_s/(H_s + 0.1)(\alpha_{si} - \alpha_{it})$, if $H_s \geqslant 0.01m$ $\alpha = \max(\alpha, \alpha_o + 0.05)$ Lynch *et al.* (1995)	Climate model (Arctic Regional Climate System model)
C_{IV}	(i)	$\alpha_{i-vis} = \alpha_o - \alpha_{i-vis}\min(atan(4H_i)/atan(2), 1) + 0.075\min(T_{melt} - T_{sfc} - 1, 0), \alpha_0 = 0.06$ $\alpha_{i-nir} = \alpha_o - \alpha_{i-nir}\min(atan(4H_i)/atan(2), 1) + 0.075\min(T_{melt} - T_{sfc} - 1, 0), \alpha_{i-vis} = 0.73, \alpha_{i-nir} = 0.33$ $\alpha_{vis} = \alpha_{i-vis}(1 - H_s/(H_s + 0.02)) + \alpha_{s-vis}(H_s/(H_s + 0.02))$ $\alpha_{s-vis} = 0.96, \alpha_{s-nir} = 0.68$ $\alpha_{nir} = \alpha_{i-nir}(1 - H_s/(H_s + 0.02)) + \alpha_{s-nir}(H_s/(H_s + 0.02))$ $\alpha = 0.53\alpha_{vis} + 0.47\alpha_{nir}$ Briegleb *et al.* (2004)	Climate model (National Center for Atmospheric Research Comunity Climate System Model)

H_i, H_s, T_{sfc} and T_{melt} are snow and ice thickness, surface temperature and melting temperature (273.15 K), respectively

Figure 4 shows the HIGHTSI calculated albedo compared with SHEBA observations. From the observed albedo, we clearly see the linkage between the changes of surface albedo and snow and ice melting. Until day around 475 (20 April, 1998), the surface remained snow covered and the albedo was fairly constant (0.85). From day 476 to 531 (15 June, 1998), the surface albedo decreased from 0.85 to about 0.6. During this period, snow was melting and elt ponds may have formed. After day 531, the ice was under continuous melting until the autumn freezing up in early August. The strong oscillations of albedo between days 476 and 531 were probably due to the effect of snowfall. During the ice-melt period (days 531—590), the variation of albedo was about 0.1 (0.6 - 0.7). Such albedo changes were probably linked with the development of melt ponds[22]. According to in situ records, the on set of snowmelt occurred on day 514 (29 May, 1998), so the actual time window for snowmelt was just about 17 days (days 514—531).

The simple albedo schemes in category I were not able to represent the temporal variability of albedo. The albedos in category II show large oscillations probably in response to the change of calculcated surface temperature. However, there was large bias between observed and modelled albedo. The albedos in category III in general follow the temporal variability of measured albedo, particularly (g) of Pirazzini *et al.* (2006)[19], which is modified from Flato and Borwn (1996)[18], (f). The albedo from the most sophisticated scheme (i) also follows the observed variability, but there was a systematic bias of 0.1. The calculated minimum albedo was about 0.5. It is close to the albedo of melt ponds, which typically varies from 0.42 to 0.56[23]. Hence, the albedo of (i) was even closer to realty, although it showed differences compared with locally measured albedo.

The observed (gauge 69) and modelled snow thicknesses using various albedo schemes are shown in Figure 5. The onset of snow melting was directly affected by the albedo parameterizations. According to these model experiments, we may conclude that the simple snow albedo (e.g. category I) may work as well as some of the more complicated albedo schemes (e.g. categories III and IV). The model run with albedo parameterization (b) most accurately catches up the timing of the snow melt. This is because the albedo was fixed to 0.75 for melting snow in (b); this value was just the same as the average albedo during the actual snow-melt period (day 514—531). The results suggested that the model run with albedo scheme in category II yield large errors, i.e., the snowmelt onset was too early compared with the measurements. The modelled snow thickness is improved when the effect of Tsfc on albedo is eliminated (category III). The modelled surface temperature is normally liable to errors. These errors may produce an artificial ice-albedo feedback, i.e., errors of surface temperature enhance the error of albedo and further enhance the error of mass balance.

The observed and modelled total ice thicknesses are given in Figure 6. It appears that during the freezing season, all modelled ice thicknesses match observed value quite well. The largest differences were found during the melt season. The model results from the albedo category II have largest errors. These were mostly due to the fact that the incorrect surface albedo triggers an artificial feedback, which lead to early onset of ice melt, particularly for cases (c) and (e). All simulations produced less ice grownt than observed between days 430 and 520. This is probably due to underestimation of snow and ice conductivities in HIGHTSI. Further analysis indicated that differences of modelled ice thickness during summer season were mainly due to surface melting owing to the differences in albedo values. The ice bottom melting also slightly contributed to errors in the total modelled ice thickness.

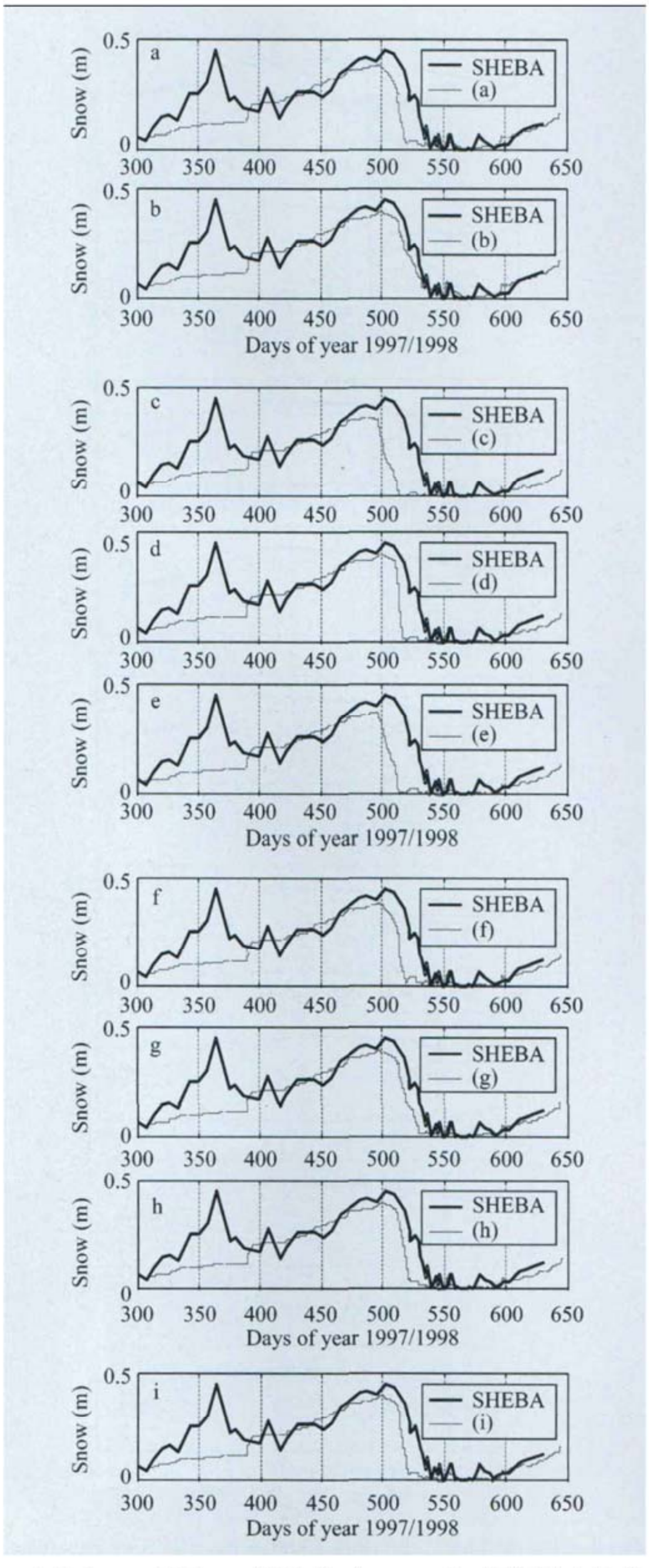

Fig. 5 The HIGHTSI modelled snow thickness (thin line) versus the SHEBA individual station measurement (thick line) at gauge 69. Various albedo schemes were applied in the model runs (Figure 4).

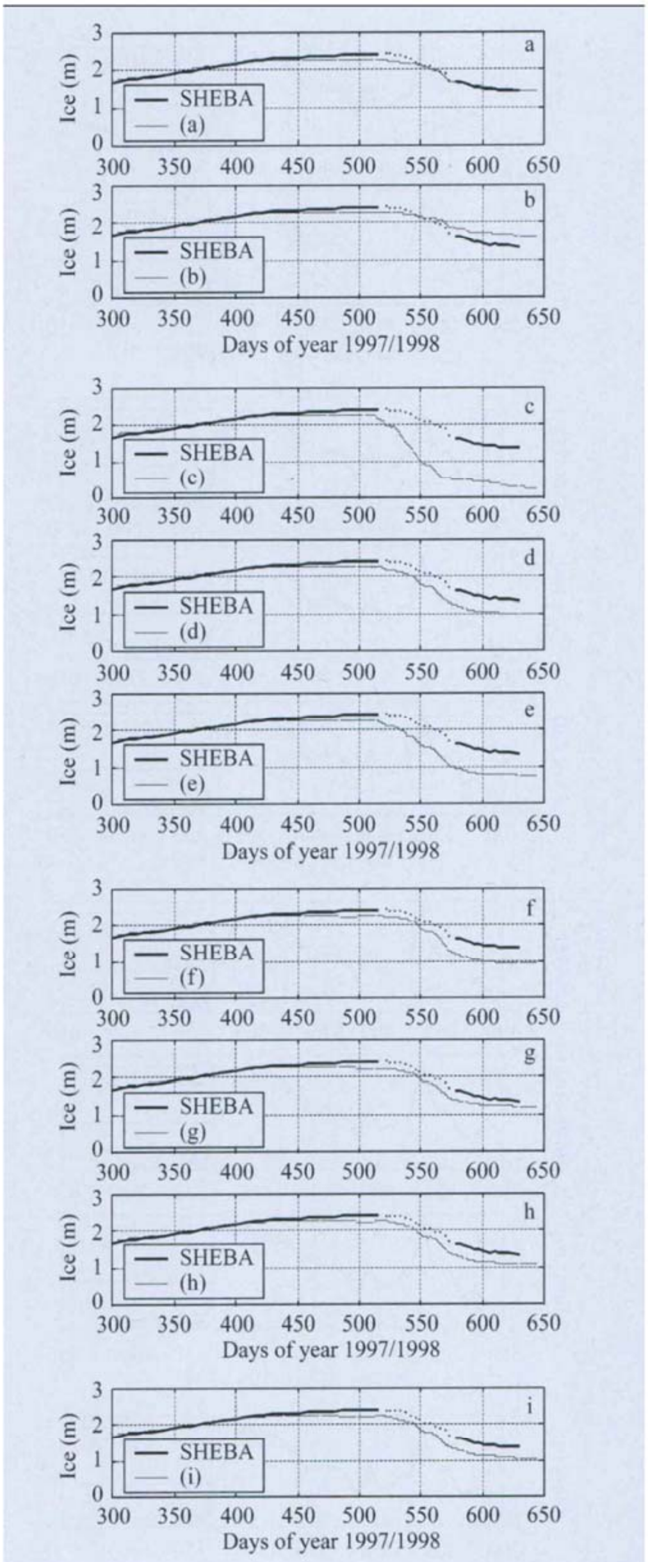

Fig. 6 The HIGHTSI modelled ice thickness (thin line) versus the SHEBA measurement (SIMIP2 data). Various albedo schemes were applied in the model runs (Figure 4).

It has been found out that snow may contribute to the ice mass by a procedure called superimposed ice formation[13,14,24,25]. During the snow melt season, the melting snow can re-freeze at the snow-ice interface. This procedure may increase the total ice thickness before the ice starts to melt.

During the melting season in SHEBA, the solar radiation was strong and pentrated into snow and ice leading to sub-surface melting. A high spatial resolution is needed to well simulate the exponential distribution of solar radiation within snow and ice. We made further model sensitivity studies to investigate the importance of superimposed ice formation and spatial resolution in the ice model. We made additional model experiments with the following conditions: (i) without taking into account the superimposed ice formation and (ii) with a coarse spatial resolution of only 3 layers in snow and 3 layers in ice.

The time series of observed and modelled ice surface melting and total ice mass balance for these model runs are shown in Figure 7. The HIGHTSI model run with a high spatial resolution is closer to the observed ice melting in the beginning. The coarse resolution model run has a more rapid surface melting compared to the observations. The high resolution model run underestimated some 15 cm surface melting, while the coarse resolution model run produced some 5 cm overestimation of surface melting. Note that the albedo proposed in SIMIP2 data sets was the area average value, in which the effect of melt ponds was not considered. In the absence of melt ponds the summertime surface albedo usually does not fall below 0.56[10]. In other words, for high resolution model, if we had taken into account the effect of melt ponds on albdo, the modelled ice surface melting would have been closer to the observations (decrease of albedo would increase the melting and overcome the underestimation of the mass balance). For the coarse resolution model, however, the surface ice melting would be even more overestimated.

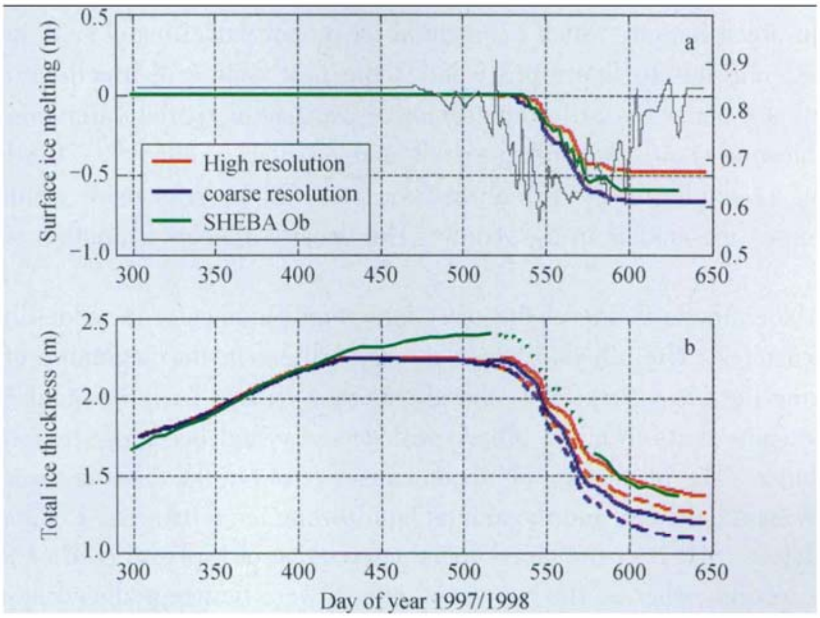

Fig. 7 HIGHTSI Modelled surface ice melting and the total ice mass balance compared with the observations. The model runs were carried by a high (red) spatial resolution (30 layers in snow and ice) and a coarse (blue) spatial resolution (3 layers in snow and ice). The SHEBA observations are given as green lines. The thin black line in the upper panel is the observed surface albedo during the SHEBA year. The dashed lines in the lower panel are the model results without taking superimposed ice formation into account.

Figure 7b demonstrates that the model runs with superimposed ice formation taken into account are in better agreement with the observations especially during the summer ice melt season. During days 455—510, the observed increase of ice thickness was not very well reproduced by the HIGHTSI. According to SHEBA measurements, there was a very cold period during that time. The air temperature dropped below −20°C for several days (Figure 1b). The growth of ice probably occurred at the ice-ocean interface. The failure of the HIGHTSI ice growth is perhaps related to the fact that the snow heat conductivity applied was underestimated. According to Huwald *et al.* (2005a,b)[6,11], the active heat conductivity of snow could be as large as 0.7 W/mK compared with the widely used value of about 0.31 W/mK.

4 Conclusions

We studied the seasonal-scale sensitivity of modelled snow and ice mass balance to paremeterization of surface albedo, model resolution, and oceanic heat flux. The model simulations were carried out using the SHEBA atmospheric and oceanographic observations as external forcing, and validated against SHEBA observations on snow and ice thickness, temperature, and albedo. The results indicated that the combination of improved parameterizations for albedo and superimposed ice formation together with a high vertical resolution improves the simulation of the annual cycle of sea ice mass balance. We stress the following conclusions.

Precipitation is an external forcing for thermodynamic sea ice models. To minimize the inaccuracy in precipitation, which is essential for proper modelling of snow and ice seasonal mass balance, one has to figure out what is the best source of precipitation data. Point measurements are not necessarily representative because of spatial variations and gauge errors due to blowing snow. According to this and previous studies[26], the ECMWF short-term forecasts (included in the reanalysis) for snow fall are reasonably accurate to be used as forcing for sea ice models in the Arctic. The density of snow is another issue that needs attention.

The surface albedo is one of the most important parameters in modelling of snow and ice thermodynamics. The albedo change is very critical in the beginning of the snowmelt season. During the pre-melt period, the albedo may remain fairly constant of 0.8—0.85, but when the snow starts to melt, albedo will decrease and becomes strongly coupled with the mass balance. The inaccuracy of albedo causes errors in the onset of snow and ice melt, snow and ice mass balance, and the annual equilibrium ice thickness. Compared against local observations at SHEBA, the albedo parameterization of Pirazzini *et al.* (2006)[19] yielded the best results, whereas the melt pond effects were best reproduced by the Briegleb *et al.* (2004)[20] scheme. Attention is needed to albedo schemes with a dependence on surface temperature, because the errors of modelled surface temperature may trigger an artificial albedo feedback leading to an unrealistic sea ice mass balance.

The model vertical resolution controls the accuracy of numerical simulation of heat conduction and penetration of solar radiation in snow and ice, and the surface mass balance. Coarse resolution models may configure more solar radiation to be absorbed for surface heat balance, which increases the sensitivity to changes in surface albedo and leads to an overestimation of surface ice melting. The superimposed ice formation should be taken into account for the annual Arctic sea ice mass balance. The oceanic heat flux is a critical variable in terms of sea ice mass balance. A reasonable annual cycle of oceanic heat flux is a precondition leading to successful modelling of season/annual sea ice mass balance.

Acknowledgements This study was supported by the EC-funded project DAMOCLES (grant 18509), which is part of the Sixth Framework Program of DFG (grant LU 818/1-1), and by the Natural Science Foundation of China (grants No. 40233032, 40376006).

References

[1] Perovich DK, Grenfell TC, Light B, Hobbs PV(2002): Seasonal evolution of the albedo of multiyear Arctic sea ice. J. Geophys. Res., 107(C10): 8044, doi: 10.1029/2000JC000438.

[2] Houghton JT, Ding Y, Griggs DJ, Noguer, Linden van der PJ, Dai X, Maskell K, Johnson CA (2001): Climate Change. The Scientific Basis, Cambridge: Cambridge University Press.

[3] Holland MM, Bitz CM(2003): Polar amplification of climate change in coupled models. Climate Dynamics, 21: 221 - 232.

[4] Wang J, Ikeda M, Zhang S, Gerdes R(2005): Linking the northern hemisphere sea ice reduction trend and the quasi-decadal Arctic Sea Ice Oscillation. Climate Dyn., 24: 115 - 130, doi: 10.1007/s00382-004-0454-5.

[5] Flato GM(2001):. Arctic Ocean Model Intercomparison Project(AOMIP). Third workshop online presentation at: http://fish.cims.nyu.edu/project_aomip/workshops/Workshop_3/flato_presentation.pdf.

[6] Huwald H, Tremblay LB, Blatter H(2005a): A multilayer sigma coordinate thermodynamic sea ice model: Validation against Surface Heat Budget of the Arctic Ocean (SHEBA)/Sea Ice Model Intercomparison Project Part 2 (SIMIP2) data. J. Geophys. Res., 110 (C05010), doi: 10.1029/2004JC002328.

[7] Cheng B, Zhang ZH, Vihma T, Johansson M, Bian LG, Li ZJ, Wu HD(2008): Model experiments on snow and ice thermodynamics in the Arctic Ocean with CHINARE 2003 data. J. Geophys. Res., 113, C09020, doi:10.1029/2007JC004654.

[8] Uttal T *et al.* (2002): The surface heat budget of the Arctic Ocean. Bull. Amer. Meteorol. Soc., 83: 255 - 276.

[9] Curry JA, Schramm J, Perovich D, Pinto JO(2001): Application of SHEBA/FIRE data to evaluation of snow/ice albedo parameterizations. J. Geophys. Res., 106:15,345 - 15,355.

[10] Curry JA, Schramm J, Ebert EE(1995): On the sea ice albedo climate feedback mechanism. J. Climate, 8, 240 - 247.

[11] Huwald H, Tremblay NB, Blatter H(2005b): Reconciling different observational data sets from Surface Heat Budget of the Arctic Ocean (SHEBA) for model validation purposes. J. Geophys. Res., 110 (C05009). doi: 10.1029/2003JC002221.

[12] Cheng B, Launiainen J, Vihma T, Uotila J (2001): Modelling sea ice thermodynamics in BALTEX-BASIS. Ann. Glaciol., 33, 243 - 247, doi:10.3189/172756401781818536.

[13] Cheng B, Vihma T, Launiainen J (2003): Modelling of the superimposed ice formation and sub-surface melting in the Baltic Sea. Geophysica, 39(1 - 2): 31 - 50.

[14] Cheng B, Vihma T, Pirazzini R, Granskog MA (2006): Modeling of superimposed ice formation during spring snow-melt period in the Baltic Sea. Ann. Glaciol., 44: 139 - 145.

[15] Vihma T, Uotila J, Cheng B, Launiainen J(2002): Surface heat budget over the Weddell Sea: Buoy results and comparisons with large-scale models. J. Geophys. Res., 107(C2): 3013, doi:10.1029/2000JC000372.

[16] Cheng B(2002): On the numerical resolution in a thermodynamic sea ice model. J. Glaciol., 48

(161): 301 - 311, doi:10.3189/172756502781831449.

[17] Lynch AH, Chapman WL, Walsh JE, Weller G(1995): Development of a regional climate model of the western Arctic. Journal of Climate, 8(6): 1555 - 1570.

[18] Flato GM, Brown RD(1996): Variability and climate sensitivity of landfast Arctic sea ice. J. Geophys. Res., 101(C11): 25,767 - 25,777.

[19] Pirazzini R, Vihma T, Granskog MA, Cheng B(2006): Surface albedo measurements over sea ice in the Baltic Sea during the spring snowmelt period. Ann. Glaciol., 44: 7 - 14.

[20] Briegleb BP, Bitz CM, Hunke EC, Lipscomb WH, Holland MM, Schramm JL, Moritz RE(2004): Scientific description of the sea ice component in the Community Climate System Model. Version Three. Tech. Rep. NCAR/TN-463 + STR, National Center for Atmospheric Research, Boulder, CO, 78.

[21] Perovich DK, Grenfell TC, Richter - Menge JA, Light B, Tucker III WB, Eicken H(2003): Thin and thinner: Sea ice mass balance measurements during SHEBA. J. Geophys. Res., 108(C3): 8050, doi: 10.1029/2001JC001079.

[22] Perovich DK(1996): The optical properties of sea ice. CRREL Monogr. 96 - 1.

[23] Tschudi M, Curry JA, Maslanik JM(2001): Airborne observations of summertime surface features and their effect on surface albedo during FIRE/SHEBA. J. Geophys. Res., 106 (D14): 15,335 - 15,344.

[24] Nicolaus M, Haas C, Bareiss J(2003): Observations of superimposed ice formation at melt-onset on fast ice on Kongsfjorden, Svalbard. Phys. Chem. Earth, 28(28 - 32): 1241 - 1248.

[25] Granskog MA, Vihma T, Pirazzini R, Cheng B (2006): Superimposed ice formation and surface fluxes on sea ice during the spring melt-freeze period in the Baltic Sea. J. Glaciol., 52 (176): 119 - 127.

[26] Bromwich DH, Fogt RL, Hodges KI, Walsh JE(2007): A tropospheric assessment of the ERA-40, NCEP, and JRA-25 global reanalyses in the polar regions. J. Geophys. Res., 112(D10111), doi:10.1029/2006JD007859.