Respond to Review of J. Weiss 14 March 2012

Review of « Albedo of the ice-covered Weddell and Bellingshausen sea » by A. I. Weiss et al., submitted to *The Cryosphere*

1.) Respond to Main comments

1.1.) The reviewer would like to know to what extent are the measurements performed along several flight tracks during two summers (2007 and 2008) are representative of the sea ice conditions (average as well as associated variability) in this region ?

The associated variability of the measurements in the three defined regions is illustrated in the data of Table 1. We believe that the averaged measurements from the flight tracks are representative because the sea ice conditions during these two years are representative for the recent decade in summer. Ice concentration and the area of first year and multi-year sea ice can be estimated from passive micro wave imagery. We included in Section 3.1 that analysis of 28 years of Antarctic sea ice data derived from satellite passive microwave radiometers (Cavalieri and Parkinson, 2008) showed that in the western Weddell Sea the mean sea ice concentration in February is between 90-100 % and that the sea ice concentration in the northern part of the Bellingshausen Sea is much lower and can vary from ≤ 12 % up to 100 %. This high sea ice concentration in the Weddell Sea and high variability in sea ice concentration in the Bellingshausen was also observed in out data set. Zwally et al. (2002) discussed the Antarctic sea ice variability. The decadal scale sea ice change has been small, although the sea ice cover varied from year to year. They found a positive sea ice extend trend in the Weddell Sea (1.4±0.9 %) and a negative trend in the Bellingshausen-Amudsen Sea (-9.7±1.5 %) for the 20 year period 1979-1998. Zwally et al. (2002) found that decadal-scale sea ice changes have been smaller and more difficult to ascertain with statistical significance. The type of sea ice for the tree main areas we defined for this study are common in these areas: In the last ten years muli-year pack ice was mainly observed in the Western Weddell Sea and in the Southern part of the Bellingshausen/Amundsen Sea, first year ice in the northern part of the Bellingshausen Sea in February. The sea ice conditions we observed in the southern part of the Western Weddell Sea are also representative for this area: The Ronne Polynya in the South-Western part of the Weddell is a coastal polynya that habitually forms off the Ronne Ice Shelf (Renfew et al., 2002). In the Weddell Sea it has been estimated that the area coverage of the polynyas and leads is about 5% (Schnack-Schiel, 1987).

1.2.) The reviewer asked how the results can be used to improve our understanding of sea ice albedo and its parameterization in climate models? In other words, to what extent the 3 temperature-albedo relationships proposed in table 3 can be used? The fact that 3 different relationships are proposed for 3 different situations (defined on a geographical basis as well as on some loosely defined ice conditions) seems to be a first answer.

We excluded the three functions which were determined from our data from Table 3. We used the data, on the one hand, to determine a spatial averaged albedo values. On the other hand, the data helped to verify published albedo parameterisation. This verification can help to interpret GCM albedo simulation, which uses this parameterisation for sea ice areas, which show a mixture of new, young sea ice, first year ice and multi year pack ice.

1.3.) The reviewer states that if field measurements of albedo in this region are scarce, h imagines that satellite (e.g. MODIS) data can be used there. Actually, why the authors did not try to compare their data to MODIS data? This could be a way to deal with the problem of the measurement scale.

We included in Section 5 that measurement of sea ice albedo and temperature are possible with optical sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS). Albedo and sea surface temperature data from satellite measurements have got the advantage to give sea ice conditions as effective value for the satellite footprint. The data from the satellite gives a larger area coverage than averaged data from the smaller flight path. We included in Section 5 that the averaged albedo values from the aircraft measurements can only be approximately assumed to be as effective albedo value for these areas. The satellite footprint for MODIS is in the range of 1 km in polar areas, but lack of special and temporal coverage can be due to clouds. The aircraft data in combination with visible observation and video footage gives the possibility to distinguish between patches of thin ice and open water. Moreover, aircraft measurements allow taking measurements during cloudy or partly cloudy conditions. The main reason why we used for this study aircraft measurements is that we wanted to investigate multiple scales of the temperature and albedo field of the sea ice areas around the Antarctic Peninsula. An advantage of aircraft measurements is that it is possible to determine from the spatial measurements local as well as spatial averaged sea ice parameters. The high sampling frequency of the aircraft instruments, which is described in Section 2.2, allows the determination of the sea ice parameters in local scales, which is in the order of 10^{th} of meters. From this data we determined the percentage of area covered by a certain sea ice albedo range in (new) Figure 3. We included in Section 5 an extended discussion of the goal that we wanted to investigate multiple scales of the temperature and albedo field of the sea ice area around the Antarctic Peninsula. We included that we determined the percentage of the area covered by a certain sea ice albedo range (Fig. 3) and the averaged albedo of the three areas adjacent to the Antarctic Peninsula (Table 1 and 2). The distribution of the albedo values reflects that all main sea ice areas show an alternation of young and old, snow-covered and bare sea ice. The regional variation of the mean sea ice albedo is mainly due to the regional variation in the mixture of ice types and its snow cover. Figure 3 shows that all sea ice areas are characterized by spatial heterogeneity of the albedo over the entire albedo range. This albedo heterogeneity affects strongly the radiation budget of the sea ice areas. The aircraft measurements show that the subgrid-scale variability of the albedo (which is also the sub-footprint-scale of the satellite) can be as small as a few meters. In combination with a spatial heterogeneity of water fraction or snow cover on larger scales this may result in an area-averaged albedo, which is fundamentally different from the albedo at a particular point. We included in Section 5 that different methods were developed to describe the subgrid-scale surface albedo heterogeneities in atmospheric models. We state in Section 5 that in this study we determined from the local scale heterogeneity of the albedo the averaged albedo for three sea ice areas around the Antarctic Peninsula. The averaged albedo value can be approximately assumed to be the effective albedo value for these areas. The effective albedo is needed for comparison with model predictions and/or satellite data. The albedo and temperature data along a flight path can be used to validate satellite data. We included this as a statement in the discussion in Section 5. but e did not include a satellite validation in the manuscript because we think this is not in the scope of this paper.

1.4.) The reviewer pointed out, that the authors stress the fact that surface temperature only explain a small part of the sea ice albedo variability, whereas the ice thickness or snow are likely important factors. But, still, they propose linear temperature-albedo functions considered as "typical".

We excluded the linear temperature albedo function from our data set (in Table 3 and in the text) and excluded from the text that linear temperature albedo functions are 'typical'. We listed in Section 4.2 examples of coupled ocean atmosphere models, which are participating in the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC-AR4, Randall et al., 2007) and which use a temperature function to parameterize the albedo. These models are the UK Met Office Hadley Centre Model (UKMO HadCM3, Gordon et al. (2000)) and the General Circulation Model (GCM) of the Max-Planck-Institute for Meteorology model ECHAM5/MPI-OM, 2005 (Roeckner et al., 2003). However, in Section 4.2 we do not attempt to investigate the accuracy of the albedo performance of all models participating in the IPCC-AR4. But we rather aim to provide a case study for a comparisons of published linear temperature albedo parameterizations with the data we observed in the Weddell and Bellingshausen Sea. We mentioned the existence of more complex albedo parameterization, such as the parameterization of the Los Alamos Sea ice model (CICE). CICE predicts the albedo with a complex parameterization including temperature, spectral bands, thickness of sea ice and snow depth. However, for a determination or validation of such complex albedo parameterization further area-covering observations of additional surface parameters, like averaged sea ice thickness and snow conditions have to be conducted in the sea ice areas of the Antarctic Peninsula.

1.5.) The reviewer states that the authors also insist very much on the difference between Arctic and Antarctic (and stress that albedo measurements in the Antarctic are limited – see his comment above about satellite data). He agrees that differences exist between the Arctic and Antarctic sea ice cover (amount of perennial sea ice, boundary conditions, melt ponds, ..) However, he guesses that a significant amount of work has been performed on the relationship between albedo, surface temperature and others factors, in the Arctic. He pointed out that these works are not really discussed in the present manuscript, giving the feeling that Antarctic sea ice is very special in terms of sea ice physics.

In order to discuss the work that has been performed to study the albedo in the Arctic in more detail, we additionally included in the paper:

1.) A quotation of the work by Wang and Zander (2011) about the Arctic and Antarctic diurnal and seasonal variations of snow albedo. In Section 3.1 we included their investigations on the cloud effect on the albedo.

2.) A quotation of the paper of Hanesiak et al. (2001) who investigated the local and regional observations of Arctic first-year sea ice. We included in Section 4.3 that they found in their study that meld ponds are characteristic for Arctic sea ice in summer.

3.) A quotation of the work by Lui et al. (2007) in the Summary Section 5, about the evaluation of snow/ice albedo parameterizations and their impacts on sea ice simulations. We included that they showed that the snow/ice albedo is function of surface characteristics, spectral bands, solar zenith angle and atmospheric properties. We included in the Summary section that they tested albedo parameterization with depends not only on surface temperature, but also on surface type (snow or ice), snow depth, ice thickness and spectral band by comparing them to in-situ measurements of the Arctic Surface Heat Budget of the Arctic Ocean (SHEBA) project. Their study showed that the simulated surface albedo differed substantially in dependence of the complexity of the used parameterization. By using a more complex albedo parameterization a more realistic ice distribution can be predict for the Arctic sea ice area. However, for a determination or validation of such complex albedo parameterization for the sea ice areas adjacent to the Antarctic Peninsula further area-covering observations of additional surface parameters, like averaged sea ice thickness and snow conditions have to be conducted.

2. Respond to other comments

2.6.) P 3264, L5-15: The reviewer states that the field of view of the IRT is given but not of the pyranometer and the video camera? He asked to make clear whether the field of "view" of the pyranometer and the IRT are equivalent and whether the field of view of the IRT is much larger (~100 m ?) Moreover, the reviewer asks to comment on the impact of different viewing angles when correlating albedo and temperature measurements and/or to precise if an averaging procedure has been used on IRT data before the comparison with albedo data. Is the logging frequency high enough to ensure a continuous record along the track (i.e. an overlap of successive fields of view) ?

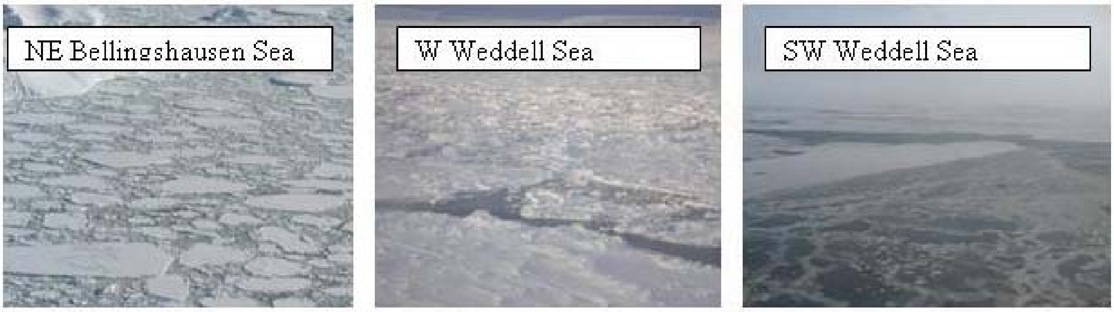
We mentioned on page 3263 line 23/24 that the radiometers (i.e. Pyranometers and Pyrgeometers) have a 2π- viewing angle. To state it clearer we included in the revised version that this means that the radiometers have got a hemispheric view. We changed the sentence on page 3263 line 23/24 to: 'The radiometers have got a 2π viewing angle, i.e. a hemispheric view.' The field of view of the IRT is described on page 3264, line 11. The short and longwave radiometers have therefore a larger field of view than the IRT. The impact of the differences of the field of view of the radiometer and the IRT is described in Section 2.3, pp 3265, line 19-27: 'Due to the fact that the field of view of the IRT is smaller than that of the pyranometers an over- or underestimation of the irradiance for the sea ice area the IRT is detecting can result. This would be the case in particular for sea ice areas, which show a strong heterogeneous sea surface due to a mixture of water or thin dark ice and solid white sea ice. However, most of our measurements presented in this study were conducted at low surface temperatures and over relatively compact sea ice with a small water fraction and we combined additionally video footage to the radiation measurements, which allows often distinguishing between thin dark ice and open water patches.' The logging frequency of the radiometers and of the IRT was 10 Hz. At a flight height of 135 m we would had maintain an exact coverage of the surface temperature with the IRT. We didn't use a different averaging of the surface temperature and albedo data. The averaged data, which are shown in Figure 4, of surface temperature and albedo are averaged for temperature bins. The data that are shown in new Figure 5 are averaged over entire flights, in order to upscale them to a range of a common model grid box.

2.7.) Section 2.3: The reviewer pointed out, that sea ice concentration is deduced using thresholds for surface temperature and albedo. This may have an impact when looking at correlations between sea ice concentration in one hand, and albedo or temperature on the other hand (Figure 3). He would like to know, whether the authors try to estimate sea ice concentration from the video record ? L 13-15: what is the combination used ?

We did not apply an image processing techniques of the video footage to the determination the sea ice concentration, because the quality of the footage where too low, i.e. the video footage was in these two flight campaigns out of focus. However, we used additional the video footage in cases were we measured low albedo values in combination with surface temperatures near the freezing point. In such cases the video footage helps to decide visibly whether low albedo values have to be assigned to open water or new ice. We included this in Section 2.3. The video footage show in case of open water often clearly ripples on the water surface. We excluded (previous) Figure 3 from the manuscript, but remain its main message in the text, which states that we did not observed any correlation between area mean albedo and ice concentration. We do believe that the reason for the low correlation is that our measurements were taken in compact sea ice areas, with very small water fraction. We included a qualitative error estimation of the sea ice concentration, as described in the respond to Reviewer 1.

2.8.) P3268, L27: the reviewer states that it seems reasonable, that the albedo is strongly controlled by the ice thickness and snow cover and that the temperature is a good proxi for these parameters, but it is not really clear from Figure 2. He would like to have more quantitative arguments mentioned.

We excluded the scatter plots in Figure 2 and shorten the discussion to Figure 2. We explain on the basis of Figure 4, which shows the bin-averaged data, that the examples reflect that the albedo is strongly controlled by the ice thickness and snow cover and that the temperature is proxy for these parameters. We state that thicker ice with snow cover, like pack ice, has a lower surface temperature and has in general a higher albedo in comparison to very thin, dark nilas ice, which can be found in the polynya region and on just-frozen leads. This thin ice, without snow cover, shows relatively warm temperatures near the freezing point and a low albedo. Perovich and Grenfell (1981) showed in laboratory experiments that when young sea ice like nilas becomes thicker the albedo increases fast. The reason is that with the decrease in ice temperature the amount of brine in the sea ice changes as well, which causes a change in its radiative properties. We additionally include that the temperature acts as proxy for the radiative properties of the snow cover and its evolution. Snow metamorphosis is influenced by the temperature. Colder and young snow has in generally smaller grains sizes than warmer and older snow. An increase in the average radius of the grains increases the length of a photon's travel path through the ice and decreases the number of opportunities for the photon to scatter out of the snow pack. This increases the probability of the photon being absorbed and reduces the surface albedo (e.g. Gardner and Sharp, 2010).



New Figure 2: Pictures of typical sea ice conditions during the field campaign in the North-Eastern Bellingshausen Sea (left panel, 26 Feb 2007), the Western Weddell Sea pack ice area (middle panel, 16 Feb 2007), and the South-Western Weddell Sea Ronne Polynya area (right panel, 25 Feb 2007).

2.9.) Section 4.1: the title of this sub-section seems a bit overstated. Where such "impact" is analyzed ?

We change the title of this sub-section to 'The use of mean albedo in numerical model studies'.

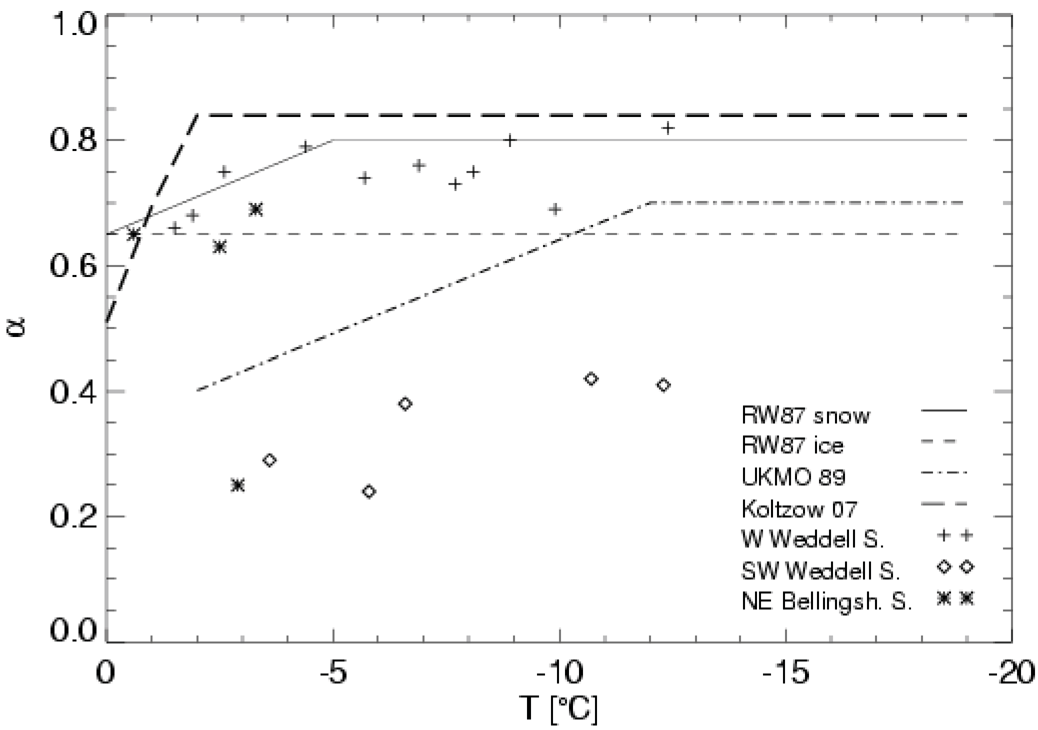
2.10.) Section 4.1: The reviewer states, that the authors discuss their results in comparison with several albedo parameterizations listed in table 3, OK. It would be interesting to know, which kind of parameterizations are used in current climate models (such as those of the CMIP3 or CMIP5 exercises).

As we already stated under point 1.4, we listed in Section 4.2 examples of coupled ocean atmosphere models, which are participating in the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC-AR4, Randall et al., 2007) and which used a temperature function to parameterize the albedo. These models are the UK Met Office Hadley Centre Model (UKMO HadCM3, Gordon et al. (2000)) and the General Circulation Model (GCM) of the Max-Planck-Institute for Meteorology model ECHAM5/MPI-OM, 2005 (Roeckner et al., 2003). However, in Section 4.2 we do not attempt to investigate the accuracy of the albedo performance of all models participating in the IPCC-AR4. But we rather aim to provide a case study for a comparison of published linear temperature albedo parameterizations with the data we observed in the Weddell and Bellingshausen Sea. We mentioned the existence of more complex albedo parameterization, such as the parameterization of the Los Alamos Sea ice model (CICE). CICE predicts the albedo with a complex parameterization including temperature, spectral bands, thickness of sea ice and snow cover (Hunke and Lipscomb, 2008).

2.11.) Section 4.1: the reviewer pointed out, that when comparing their measurements to climate model parameterizations, the authors are faced with a problem of spatial scale. In models, albedo or SST are defined at the scale of the grid box, i.e. several orders of magnitude larger than the scale of the measurements. So, a proper upscaling procedure should be used before comparison. A comparison with satellite data (e.g. MODIS has a 250m resolution in the visible spectral range) could be also useful in this respect. See also his general comment about the representatively of the measurements. This is an important problem that should be addressed correctly. To build their albedo-temperature relationships, the authors binned their data in bins of temperature, but did not average spatially.

The comparison of the aircraft data to the climate model parameterizations has the problem of different spatial scales, because the parameterisations are defined for model grid boxes. We averaged the albedo and temperature data spatially over each entire flight. The flights were in the range from 171 km – 634 km in the Bellingshausen Sea, from 181 km -563 km in the

Western Weddell Sea, and from 85 km – 350 in the South Western Weddell Sea. The averaged data and flight lengths are listed in Table 1. We assume that the up scaling law of albedo is basically linear from meter resolution to coarser resolutions (200 m, 500 m, 1000 m) and not significantly subject to the variation of the atmospheric conditions. This implies that the aircraft albedo measurements, which are of relatively fine resolution of some meters can be linearly aggregated to the coarser resolution of a couple of hundred meters, which is the size of common model grid box widths. We used this averaged data for the comparison with the model parameterisation in (new) Figure 5 (and not anymore the bin-averaged data). We do not use satellite data for additional up scaling, as discussed under Point 1.3. We excluded from the manuscript the determination of three new albedo-temperature relations. We compared the published temperature-albedo parameterisations in new Figure 5 with the averaged data of entire flights.



(new) Figure 5: Examples of albedo parameterization schemes, listed in Table 3, that use the surface temperature as driving input parameter: *RW87* shows the albedo parameterization scheme of Ross and Walsh (1987) for snow covered and bare ice, respectively; *UKMO89* is the parameterization of the UK Met Office GC model, as described by Ingram et al. (1989) and *Koltzow 07* a parameterization scheme for the HIRHAM model (Christensen et al, 1996) which is described by Køltzow (2007), Version 1, i.e. with the assumption of no melt pond fraction. The parameterizations are shown only for temperatures below zero degrees. Additionally shown are the mean temperature albedo values of this study for the Western Weddell Sea ice area, South-Western Weddell Sea ice area and North-Eastern Bellingshausen Sea in summer averaged over entire flights as listed in Table 1.

2.12.) Section 4.2: the reviewer would like to know, how the surface temperature measurements from the IRT can be compared with 10m SSTs of models or re-analyses?

The IRT measures the surface temperature of the sea and the sea ice. Sea surface temperature (SST) measured with the IRT is the brightness skin water temperature of the ocean surface or sea ice surface. This can be significant different from the 10m ocean water temperature or 2 m height air temperature from re-analysis. But these temperatures are normally not the ocean model temperature of the SST. We do not use the IRT temperatures to test parameterizations, which uses the air temperature as input parameter.