Interactions between clouds and sea ice in the Arctic

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Summary: The feedback between clouds and sea ice got more importance in the last years, because of the declining Arctic sea ice extent. Previous observations show the formation of low clouds over newly formed open water. These low clouds are very important for the Arctic Energy Budget, because they warm the surface. This leads to increasing temperatures and stronger sea ice loss.
To assess the relationship between sea ice cover and cloudiness, satellite observations by DARDAR were compared with both global climate reanalyses ERA–Interim and MACC. The analysis focuses on 2007 – 2010 and the relationship between different parameters from the different datasets. It is found that the reanalyses only poorly approximate the cloud cover in the Arctic. Consequently no strong correlation was found for the time period 2007 – 2010.

Zusammenfassung: Das Wolken–Albedo–Feedback in der Arktis gewann in den letzten Jahren immer mehr an Bedeutung aufgrund des Rückganges der Meereisfläche. V orhergehende A rbeiten z eigten d ie B ildung v on t iefer B ewölkung über kürzlich aufgebrochenen Meereisstellen. Diese tiefen Wolken sind sehr wichtig für das arktische Energiebudget, wegen des Erwärmens der Oberfläche. Daraus folgt ein Anstieg in der bodennahen Temperatur und ein verstärkter Rückgang des Meereises.
Um den Einfluss d er M eereiskonzentration a uf d ie Wolkenbildung z u untersuchen, werden in dieser Arbeit Satellitendaten von DARDAR mit den beiden globalen Klimareanalysen Era–interim und MACC verglichen. Analysiert werden Daten aus den Jahren 2007 bis 2010 und für verschiedene Oberflächenbedingungen werden Korrelationen der einzelnen Datensätze erstellt. Es hat sich gezeigt, dass die Darstel-lung der Wolkenbedeckung in der Arktis durch die Reanalyse Daten nicht geeignet ist. Aus diesem Grund wurden keine signifikanten Korrelationen in der Zeitspanne von 2007 bis 2010 gefunden.

1 Motivation

Clouds play an important role in the energy budget of the Earth and are one factor, which is not well understood and quantified (Wielicki et al., 1995; Boucher et al., 2013; Curry et al., 1993; Quante, 2004). For predicting the future climate it is very important to understand cloud interactions with surface and atmosphere. One of these processes is the feedback between sea ice and cloud properties, which can be best studied in the Arctic.
Due to its stable atmosphere and characteristic surface, the Arctic may show a special feedback between clouds and the surface. As shown by Beesley and Moritz (1999), the Arctic is cloudy 80 % of the year and by contrast to the general cooling effect of clouds, in the Arctic the clouds heat up the atmosphere stronger than they cool the Earth's surface. Only during a short time in polar summer the reflection of incoming radiation is higher, so that the clouds cool the Earth's surface (Shupe and Intrieri, 2004). Additionally because of the variability of the surface and the boundary layer, it is possible to observe the formation and the dispersion of clouds over open water and ice. In this case it is very important to take a closer look on the albedo because at the ice edge there is a big variability of the reflectiveness. This leads to a balancing act between warming and cooling the atmosphere.
Also strongly associated with the warming of the Arctic is the decline of sea ice. Cuzzone and Vavrus (2011) found out, that the years 2007 to 2010 have the lowest sea ice concentration on record over the period from 1979–2010. The record minimum was observed in September 2012 with around 37 % less sea ice than the average over the years 1979 until 2006. Besides, the annual cycle of the sea ice varibility is important for the stability of the boundary layer. Furthermore the temperature in the Arctic rises two times faster than in the mid–latitudes. These effects are called Arctic Amplification.

1.1 Satellites and Instruments

The A–Train describes a number of satellites which fly from south to north in 705 km and cross the equator every day at 1.20 pm local time. Here data records of the satellites Aqua, CloudSat and CALIPSO are used. They fly right behind each other, hence with the short time interval between them it is possible to observe the same situation of the atmosphere with various measurements in different perspectives.
From Aqua the data of the *Advanced Microwave Scanning Radiometer* (AMSR–E) were used. It is a passice microwave radiometer with twelve channels and six frequencies (6.9, 10.7, 18.7, 23.8, 36.5 and 89.0 GHz), which combines it to measure the upwelling brightness temperature of the sub–satellite track. The final product taken was the ice concentration, which is derived from the brightness temperature is gridded on an elliptic polar stereographic grid with a cell spacing of 12.5 km.
For the clouds the data record DARDAR was used. This is a assembled product of the *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Oberservation* mission (CALIPSO) and *CloudSat*. CALIPSO provides measurements of all airborne particles, such as cloud and aerosol particles. Therefore an active lidar is used, which contains passive infrared as well as visible imagers. In addtion to the lidar measurements CloudSat provides information collected with a radar instrument. Together both instruments give a good overview of the atmospheric conditions, because the lidar can detect thin clouds, and the radar can look through these

clouds and collect data further down in the atmosphere, such as water clouds and precipitation.

1.2 Reanalysis

For comparison two data records of the *European Centre for Medium–Range Weather Forecasts* (ECMWF) are used. The first is ERA–Interim and the other one is *Monitoring Atmospheric Composition and Climate* (MACC). Both are global atmospheric reanalyses. ERA–Interim is based on the IFS (Cy31r2) from 2006. It contains global surface parameters and atmospheric parameters on 60 vertical levels, from the surface up to 0.1 hPa and with a spatial resolution of ∼80 km. Data are available for the time period 1 January 1979 to present and at the times 0 UTC,6 UTC,12 UTC and 18 UTC.
The second data set MACC covers the period 2003 until 2010 and is specialized on chemically reactive gases, as well as aerosols and greenhouse gases. For MACC a newer version of the IFS (Cy36r1) is used. This IFS cycle uses improvements to the cloud algorithms (Inness et al., 2013). The horizontal resolution covers the troposphere and the stratosphere also of ∼80 km, globally. The difference in the calculated cloud cover between the two reanalyses is relatively small, globally and specified on the Arctic region (north of 60 °).

2 Methodology

To get a cloud cover from the satellite record, it was necessary to analyse the satellite track. For that, each time step of the satellite track was assigned to a point on an elliptic polar stereographic map of the ice fraction by AMSR–E with the map projections tool of the *National Snow and Ice Data Center* (Cavalieri and Comiso, 2014) from 1990.
In the database entry, each time step has a longitude and latitude mark and the observation values. These marks were used to transfer to a x, y–grid by converting the geodetic latitude (lat) and longitude (lon) from degree to radians (see Eq. 1). This grid has an extension of 7600 km (x–Axis) and 11 200 km (y–axis). The factor 3850 and 5350 (see Eq. 1) are in kilometre and were added, so that the north pole is in the center of the x, y–grid and ρ is the eccentricity factor.

$$y = \frac{\rho \cdot \cos(lon) + 3850}{12.5} \quad \text{and} \quad x = \frac{-\rho \cdot \sin(lon) + 5350}{12.5} \tag{1}$$

For the cloud cover, the footprint in each grid box over the Arctic were counted for cloud free and cloudy conditions, where the cloudy cases were identified using the *Cloud_Scenario* by Cloudsat and the cloud mask *Calipso_Mask* by CALIPSO. The *Cloud_Scenario* classifies the clouds according to cloud categories from 0 to 8, where 0 says there is no cloud and the values 1 to 8 describe different cloud types. The *Calipso_Mask* is able to give four different values for the detection of clouds, which evaluates the quality of the detected area. Here just cases with the value "good detected" (value=3) were counted. After the addition of both classifications, the value was divided by the sum of all clouds to get a cloud cover (see Eq.2).

$$\text{cloudcover} = \frac{\text{observations of detected clouds}}{\text{sum of all observations}} \tag{2}$$

To evaluate the cloud cover over different sea ice conditions, three cases were defined: Open water with a sea ice condition lower than 15 %, completly ice covered with a sea ice extent over 20 % and the trasition region, called edge with a sea ice concentration between 15 % to 20 %. To clarify the transition area, from the grid points which count to the edge conditions, the are was extended for 100 km in each direction of the grid point. With this division it is possible to analyse the relationship of different surface conditions and cloudiness.

3 Results

The comparison of the averaged annual cycle for the years 2007 until 2010, averaged over the region north of 60 °, is shown in Figure 1. The reanalysis data of Era–Interim (red) and MACC (blue) are following each other and are converging from August onward. They represent the same annual cycle with a minimum in the cloud cover in June and a maximum in November. However, the annual cycle of the clouds in the satellite data differ from the model cycles. In the satellite record the minimum in the cloud cover is during February (see Fig. 1), as it was described by Intrieri et al. (2002), and two maxima, one in early summer and the other in autumn. The autumn maximum is consistently found in all datasets, the reanalysis data show it in November and the satellite observations a little earlier in October.
To draw a clearer picture the spatial distribution of the cloud cover and the sea ice extent for three selected months of the Era–Interim data is shown in Figure 3 to compare the opposite results of the model and satellite data. Therefore selected were the month November, because of the strong increase in arctic sea ice in the Era–Interim data (not shown) and the month of the minimum averaged cloud cover. The minimum cloud cover differs in between the data. The satellite data of

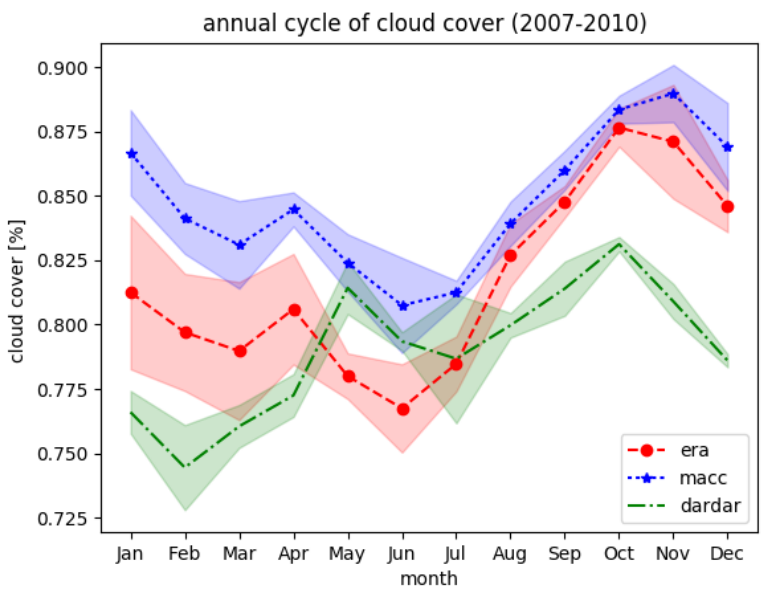
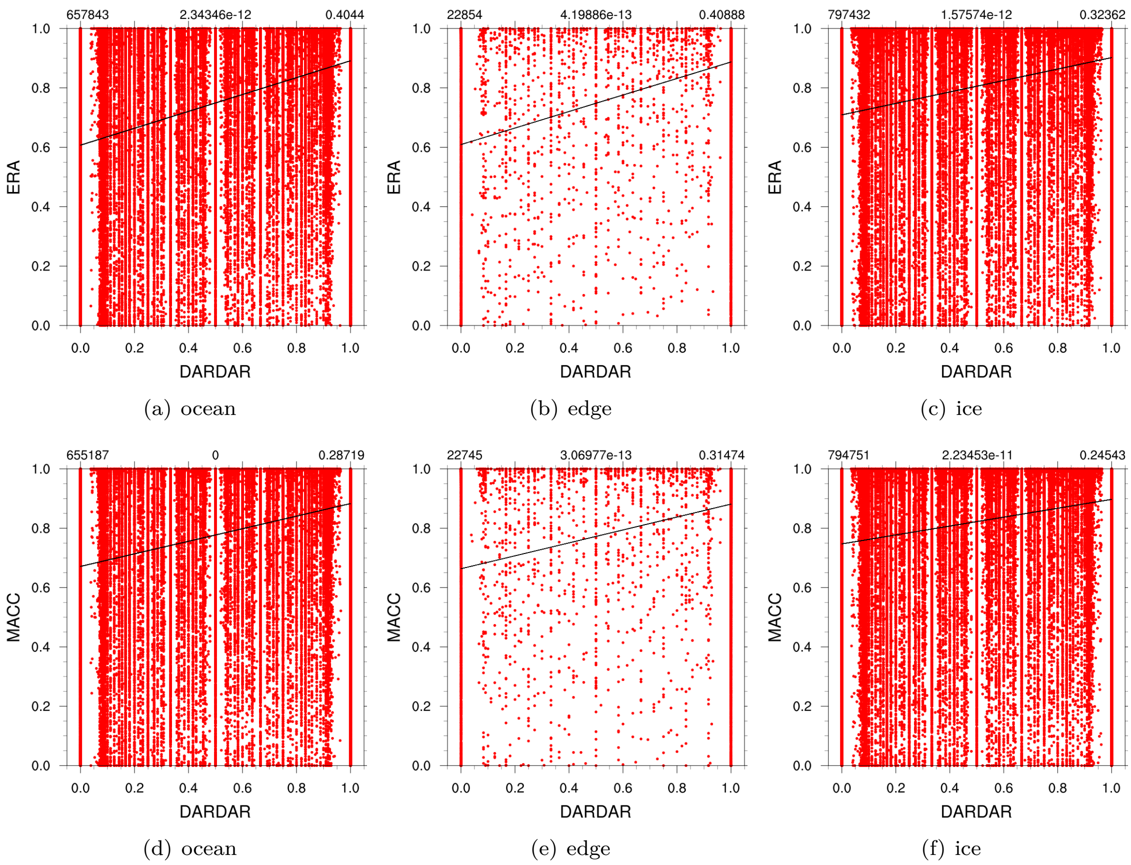


Figure 1: Cloud cover in percent over the Arctic by ERA–Interim (red), MACC (blue) and DARDAR (green) for the years 2007 until 2010. The lines show the averaged cloud cover north of 60 degree for each month and the shading the standard deviation.

DARDAR show the minimum in February and the model data in June.
For November the cloud cover of ERA–Interim over the Arctic ocean is over 90 %, except of the Beaufort Sea, there the cloud cover is around 70 % (comp. Fig. 3). North of Norway, where no sea ice exists the cloud cover reduces and over land the cloud cover is lower than over the ocean or sea ice. During the reanalysis cloud cover minimum in June (see Fig. 3, the middle panel) the cloud cover decreases with the decreasing sea ice. This could imply, that the Arctic cloud cover is not well represented in the models. As Kay and Gettelman (2009) summarized the cloud presence is mostly depending on large scale circulation pattern, but surface conditions, such as snow and ice, influence the cloud as well. The satellite data can catch the Arctic cloud cover better than the models. It can be seen, that during the chosen time interval most of the Arctic is covered with sea ice. In February the sea ice extent is on its maximum, even the Hudson Bay is ice covered. The cloud cover shows in this month a lot more variablity than in the others, see Figure 3. Compared to Figure 1 the spatial distribution shows the minimum of the cloud cover in the High Arctic. There the cloud cover is around 20 % to 30 %.

In the Figure 2 the correlation of the cloud cover between the reanalysis data and the satellite data is shown for the defined surface conditions. The number of analysed data points, in the correlation plot for each time step and each grid point, varies strongly between the surface cases. The transition area contains nearly 23.000 analysed points, but the analyse over the open ocean and ice has around



(a) ocean (b) edge (c) ice

(d) ocean (e) edge (f) ice

Figure 2: Correlation between the daily averages of the cloud cover of DARDAR and ERA–Interim (upper panel) and MACC (lower panel) over different surface conditions, for the time period 2007 till 2010 with the linear regression. On top in the left corner it shows the number of observed points, in the middle is the p–value of the Pearson's r–test and in the right corner the slope of the regression.

	MACC			**ERA-Interim**		
	r	r^2	m	r	r^2	m
ocean	0.29	0.08	0.21	0.4	0.16	0.28
ice	0.25	0.06	0.15	0.32	0.10	0.19
edge	0.32	0.01	0.22	0.41	0.17	0.28

Table 1: Correlation (r), explained variance (r^2) and slope (m) of the regression values of the comparison between DARDAR and the reanalysis data MACC and ERA–Interim.

34 times more data points. In all analysed cases it is clear that the produced cloud cover by ERA–Interim and MACC does not depend on the satellite observations, this was shown as well by Zygmuntowska et al. (2012). The corresponding measurements are strongly spread. Even when the satellite detects a cloud free condition, the model data have clouds. In all Figures 2(a) – 2(f) it is found that the cloud cover by ERA-Interim and MACC is noteworthy higher than the satellite data. On average the Era–Interim data are 60 % higher and MACC are 67 %.
The regression lines emphasize this fact by having the point of intersection with the y-axis in all cases above 65 %. Also it is discernible, that a higher DARDAR cloud cover is corresponding with an increased ERA–Interim cloud cover (comp. Fig. 2). The same applies to MACC's cloud cover. In both data records, the correlation coefficient is smallest in the ice case and highest in the ice edge case (comp. Tab. 1). The ERA–Interim correlation values are 0.08 to 0.12 higher than the MACC's correlation coefficients. For the statistical significance of the correlation coefficient the *Pearson's rtest* was used. The proportion to the ERA–Interim data for the variation of the DARDAR data is on average 14.5 % and to the MACC data it is 8.1 %. Comparing the spatial distribution of both reanalyses in the observed time periode (not shown), it is exhibited that neither ERA–Interim nor MACC show the cloud cover minimum in February/March, but in these Figures the annual cloud cycle is approximated. Especially for the central Arctic, it is visible, that the cloud cover rises in the summer months and decreases in the winter. However, for the whole region north of 60 ° in both cases, the cloud cover is nearly stable and especially for the central Arctic strongly cloudy.

4 Conclusion

In this work, a comparison between the cloud cover of satellite observations and global climate reanalysis data records over different surface conditions in the Arctic was performed. For the satellite data, the DARDAR data set was used, which provides cloud retrievals. First the data were converted to a polar stereographic grid and in a second step the cloud cover was calculated. For the reanalysis data the total cloud cover of ERA–Interim and MACC were used.
The shown annual cycle reveals the distinction between the satellite and reanalysis record. The timing of both, cloud cover yearly maximum and minimum is shifted in the model data. In the spatial distribution it can be seen, that the cloud cover of the model data are nearly homogeneously distributed over the high arctic region. Additionally no connection between the cloud cover and the sea ice can be detected in the reanalysis data. A big change can be only observed over ocean and at the coasts. This is in agreement with the results of Kay and Gettelman (2009), which discribe the change in surface as one of the main factors in the observed cloud cover change. The time correlation of daily averages over 4 years for the ERA–Interim and the MACC data showed clearly that the correlation between the data records (comp. Fig. 2) is weak.
In summary it is clearly visible, that neither ERA–Interim's cloud cover nor MACC's cloud cover mirror the observed cloud cover by satellites in the Arctic. Also these data are not convincing regarding the feedback between sea ice and cloud properties. The explaining variances for the reanalyses are too small to get a clear answer.
For future research, it will be important to take a closer look of low clouds, because stratus clouds are the most frequent cloud type in the Arctic. Kay and Gettelman (2009) proposed that clouds with a cloud top height lower than 3 km play the largest part in the Arctic energy budget and are also more influenced by the surface conditions than the higher clouds. Here the total cloud cover was used and it is possible that it is not representative. Uncertainties could be produced by cirrus clouds, or in the southern part by nimbostratus clouds. If this is the case, the spread of the correlation will be smaller for low clouds and the variance will be improved. Furthermore a regional comparison between the reanalyses and the satellite data will show if there are regions where the reanalyses data by MACC and ERA–Interim mirror better.
Also it is important to improve the reanalysis data records, to get a connection to the cloud cover measured by satellites. Therefore more measurements over a longer time period in the Arctic are necessary. Such improved datasets might then allow for a more conclusive investigation of the relationship between sea ice and cloudiness.

Appendices

Appendix A Era–Interim 2007–2011

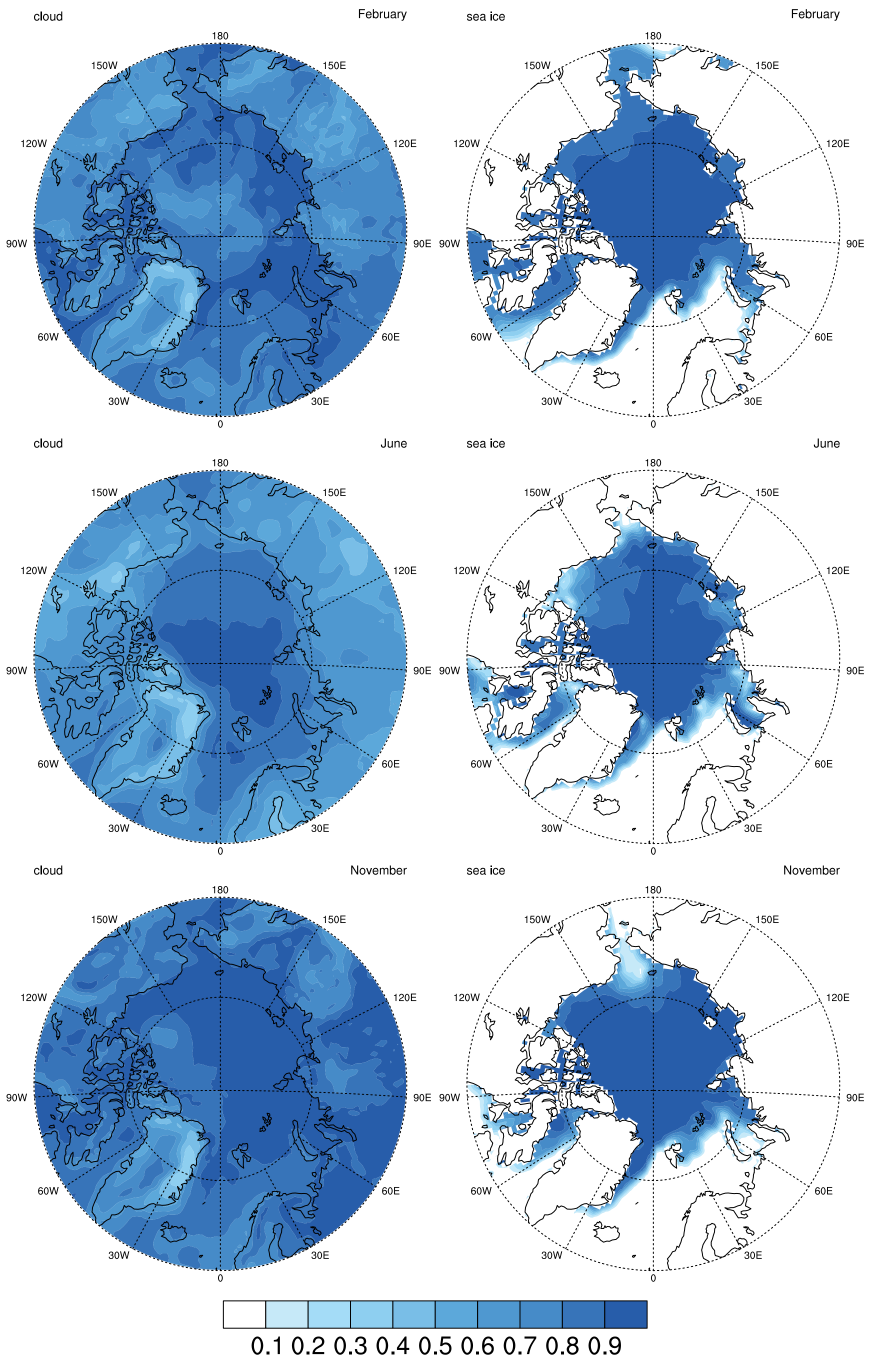


Figure 3: Cloud cover on the left hand side and sea ice concentration on the right hand side, both in percent for the Arctic ocean by ERA–Interim for the month June (upper panel) and November (lower panel) of the years 2007 until 2011.

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