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Interactions between clouds and sea ice in the Arctic

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Abstract

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 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 estimate the influence of the sea ice concentration on the cloud formation this work compares satellite observations by DARDAR with both global climate reanalyses ERA-Interim and MACC. The analysis focuses on 2007 – 2010 and correlate the different data with each other to verify a correlation of the data records for different surface conditions. It is found that the data records only poorly approximate the cloud cover in the Arctic. Consequently no strong correlation was found for the time period 2007 – 2010.
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1 Introduction

Clouds play an important role in the energy budget of the Earth, which is why the feedback between sea ice and cloud properties is very important to understand for predicting the future climate.

Due to its stable atmosphere and characteristic surface, the Arctic is a good place to observe the 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 summer, when the sun shines 24 hours a day, 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 sea ice extent. Cuzzzone and Vavrus (2011) found out, that the years 2007 till 2010 have the lowest sea ice concentration on record over the period from 1970-2010. The record minimum was observed in September 2012 with around 37% less sea ice than the average over the years 1979 till 2006 (see figure 1). Besides, the annual cycle of the sea ice variability (see figure 8) 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.

![Sea Ice Concentration 09 September 2015](www.iup.uni-bremen.de (accessed on 10.09.2015))
1.1 Arctic amplification

As mentioned above, the extreme sea ice loss and the increase of the temperature are the two most important factors for the Arctic amplification. Mostly atmospheric feedbacks are known as the essential impacts.

The most important feedback is the albedo feedback. Most of the surface is covered by snow and ice and hence white, so the incoming solar radiation is primary reflected. The albedo of snow is nearly 100 percent, but the albedo of ocean is very small. Most of the incoming radiation is absorbed by the ocean. At the sea ice edge the albedo is very variable, partly high over ice, partly low over ocean, so the average albedo is \( \alpha = 0.5 \) (see figure 2).

![Figure 2: Schematic albedo feedback. (Sabine Hörnig)](image)

When there is open water in the middle of ice expanse, the surface is much darker than the environment. In this area, the open water absorbs the radiation and so the ocean gains heat. Consequently more ice melts around the open water, which means the dark area and the ocean temperature increase and the albedo is lowered. Because of that, especially in the summer, the ocean obtains heat. This additional energy is transported back to the atmosphere in autumn. As a consequence the temperature increases. That is why the ice fraction increases more slowly during winter, so the
heat loss rises. It is called a positive feedback, which intensifies itself. Besides the annual cycles (see figure 8), the ice fraction also depends on regional influences, that is why there are some anomalies around the Arctic region. For example at the east coast of Greenland, the ice fraction increases while in other regions the ice fraction decreases, and the other way round. The reason for that is the Gulf Stream, which transports warm surface water to the poles and influences the temperature at the coast, so that it is moderate. The second important feedback is the cloud feedback. It describes the effect of clouds on the surface temperature, which can be positive and negative. Clouds absorb a part of the thermal radiation which is reflected from the ground back to space and emit its back to the ground. The result of which is that the ground gains more heat. At the top of the cloud, however, a large amount of solar radiation is reflected back to space, which leads to a cooling of the surface. Also to notice is the transmissibility or rather the optical thickness of the cloud. The thicker a cloud is, the more solar radiation is reflected back to space. In other words the albedo over the same surface increases and the less radiation is transmitted by the cloud to heat the surface. Besides the optical thickness, also the surface under the cloud is significant, because the albedo of a cloud over ice is different to that of the same cloud over open water (Coakley, 2003). When the cloud is optically thin it is possible to see the dark water under the cloud, the albedo is smaller than when the same cloud is over ice, because the cloud and ice have a similar colour. If that is the case, the reflectiveness only depends on the angle of incidence of the radiation.

1.2 Cloud formation in the Arctic

The formation of clouds depends on seasonal and geographical conditions. It is influenced by large-scale atmospheric circulation, surface properties and atmospheric conditions, like height of the boundary layer, radiation, etc. The surface fluxes of latent and sensible heat are secondary players (Kay and Gettelman, 2009), because in the stable atmospheric layering, that is wide spread in the Arctic, they are inhibited most of the times. Notably in the winter months, the atmosphere is stable because of absent solar radiation and a large sea ice extent. The biggest influence have micro-physical processes and horizontal advection. In addition the cloud feedback encourages the formation of optical depth of clouds and the cloud fraction, because its influences the solar radiation at the top of the atmosphere and indirectly the surface temperature (Curry et al., 1996).

Most of the clouds in the Arctic region are mixed-phase clouds, that means that ice and supercooled water coexist. This is possible from 0°C up to a temperature of -35°C. In this temperature range and when an ice crystal, exists the Bergeron-Findeisen process takes place. This process describes the most effective way of particle growth in a cloud. The saturation vapour pressure over ice is lower than over water, because of that supersaturation with respect to ice is more likely to be reached and thus the
available water vapour sublimates on the ice crystals and droplets shrink. The ice crystals grow at the expense of the liquid droplets. The ice particles in the cloud grow to ice crystals and when they achieve a size of 100 µm, they fall out. As mentioned above the stability of the atmosphere influences the formation of clouds. Kay and Gettelman (2009) found out, that clouds are formed in a stable, as well in an unstable atmosphere. In stable atmosphere stratus clouds form, when warm and moist air meets colder temperatures over ice. In an unstable environment convective clouds are formed by upward fluxes of moisture and heat. Cold air is transported over a warmer surface, so that moist and warm air can rise. In this case, there is a strong surface-ocean-atmosphere coupling (Kay and Gettelman, 2009). Because of the stable stratification over ice, the parametrization of clouds could be most difficult there. But at or near the ice edge where cold air outbreaks are regularly formed, the parametrization could perform good. This thesis investigate whether this is the case in the reanalyses ERA-Interim and MACC.

2 Data

2.1 Satellites and Instruments

2.1.1 A-Train

The A-Train is operated by the U.S. National Aeronautics and Space Administration (NASA) and in cooperation with the French space agency Centre National d’Etudes Spatiales (CNES). The “A” in A-Train stands for Afternoon, that is because all satellites are in a sun synchronous orbit and pass the equator at local time of 1.30 pm. The satellites fly from south to north at an altitude of 705 km and reach the pole fourteen times per day, in other words they need 100 minutes for one orbit. The leader-satellite is OCO-2 followed by GCOMW-1, Aqua, CALIPSO, Cloudsat, Parasol and Aura. Because there is just a short time interval between the satellites, it is possible to observe the same situation of the atmosphere with various measurements to different timestamps and perspectives. For that several passive and active sensors are operated on the satellites. Here data records from Aqua, CloudSat and CALIPSO are used and introduced in the following sections.

2.1.2 Aqua

The first member of the A-Train is the satellite Aqua, which flew in leading position until 2009. The mission started in 2002 by NASA EOS (Earth Observing System). Six instruments are installed on board. In this work, the Advanced Microwave Scanning Radiometer (AMSR-E), was used, which is developed by Japan Aerospace Exploration
2.1 Satellites and Instruments

**Figure 3: A-Train Constellation, source: www.oco.jpl.nasa.gov (accessed on 21.09.2015)**

Agency (JAXA). It is a passive microwave radiometer with twelve channels, six frequencies (6.9, 10.7, 18.7, 23.8, 36.5 and 89.0 GHz) and provides global measurements. It scans the footprint of the Satellite by rotating constantly about an axis ($\pm 61^\circ$) at 40 rpm and measures the upwelling brightness temperature of the sub-satellite track. The swath of the track is 1445 km wide and the measurement interval is every 10 km (5 km for 89 GHz channels) with an incidence angle of 55$^\circ$. The data of AMSR-E have a spatial resolution like the Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) together, because AMSR-E combines all channels that SMMR and SSM/I have into one sensor. 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.

2.1.3 CloudSat and CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation mission (CALIPSO) and CloudSat were added to the A-Train in 2006. They provide active observations of the Earth from space. CALIPSO flies 15 seconds in front of CloudSat and collects data about airborne particles in the atmosphere, these are cloud particles and aerosols, which play an important role in the weather and climate of the Earth. For that purpose an active lidar instrument is used, which uses passive infrared as well as visible imagers. CloudSat uses radar to measure the properties of clouds and precipitation. The data of both satellites are assembled in the DARDAR data record by the
2.2 Reanalysis

Laboratoire Atmosphère Milieux, Observations Spatiales and the Cloud Group of the Department of Meteorology, University of Reading (LATMOS). DARDAR stands for radar (CloudSat) and lidar measurements (CALIPSO). This data set includes an atmospheric feature mask and ice cloud retrievals. This mask has a resolution of 1.1 km up to a height of 25.08 km and contains a radar-lidar target categorisation. Moreover, radar, lidar and infrared radiometer measurements are collocated.

2.2 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 atmospheric and surface 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 till 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 unspecified 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 like shown in figure 4. Both global and in the Arctic the difference is very small. The maximal difference is 20%, mostly in maritime provinces. On average the difference is 5%.

![Figure 4: Difference between the cloud cover of ERA-Interim and MACC for the time period 2007 – 2010.](image)
3 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 the elliptic polar stereographic map of the ice fraction by AMSR-E with the map projections tool of the National Snow and Ice Data Center (NSIDC) 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. For getting the standard longitude (slat), the geodetic longitude was corrected with the correction factor \( cf = 135^{\circ} \).

\[
slat = \text{lat} \times \frac{\pi}{180} \quad \text{and} \quad slong = (\text{long} - cf) \times \frac{\pi}{180}
\]

In the next step several variables \( tc \), \( t \) and \( mc \) were introduced, to get the eccentricity factor \( \rho \) (see eq. 4), The x and y value of the new grid are calculated with \( \rho \).

\[
tc = \tan\left(\frac{\pi}{4} - \frac{\text{slat}}{2}\right) \cdot \left(1 - e \cdot \sin(\text{slat})\right)^{e^{-2}}
\]

\[
mc = \frac{\cos(\text{slat})}{\sqrt{1 - e^2 \cdot \sin(\text{slat})^2}}
\]

\[
t = \tan\left(\frac{\pi}{4} - \frac{\text{lat}}{2}\right) \cdot \left(1 - e \cdot \sin(\text{slat})\right)^{e^{-2}}
\]

\[
\rho = re \cdot mc \cdot \frac{t}{tc}
\]

slat = 70 : standard latitude
e = 0.081816153 : elliptic factor
re = 6378.273 : radius of the Earth
cdr = 57.29577951 : conversion constant from degrees to radians

With the equations 5 and 6 the polar stereographic grid was created. This grid has an extension of 7600km (x-Axis) and 11200km (y-axis). The factor 3850 (see equation 5) and the 5350 (see equation 6) are kilometre and were added, so that the north pole is in the center of the x,y-grid.

\[
y = \frac{\rho \cdot \cos(\text{long}) + 3850}{12.5}
\]
\[ x = \frac{-\rho \cdot \sin(\text{long}) + 5350}{12.5} \]  

(6)

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.

\[
\text{cloudcover} = \frac{\text{number of detected clouds}}{\text{sum of all clouds}}
\]  

(7)

The Cloud\_Scenario classifies the clouds according to the cloud categories, like shown in table 1. An overpass is cloudy when the Cloud\_Scenario gives a value between 1 to 8. The Calipso\_Mask is able to give four different values for the detection of clouds. In case of a good detected cloud the value is 3, for no detected cloud 6, for a medium good or bad detected cloud 4 and 5. Only the cases of good detected clouds are used here. Both cloud masks were considered and summarized. After the addition of both classifications, the value was divided by the sum of all clouds to get a cloud cover (see eq.7). The cloud cover was split in three cases depending on the sea ice concentration: open water (lower than 15\%), ice covered (higher 20\%) and ice edge (15\% till 20\%). With this division it is possible to compare the cloud cover distribution depending on the sea ice concentration. The different regions have an extension of 100km for observing the influences of different surface conditions.

<table>
<thead>
<tr>
<th>value</th>
<th>category</th>
<th>height [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no cloud</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Cirrus</td>
<td>&gt;7</td>
</tr>
<tr>
<td>2</td>
<td>Altostratus</td>
<td>2-7</td>
</tr>
<tr>
<td>3</td>
<td>Altocumulus</td>
<td>2-7</td>
</tr>
<tr>
<td>4</td>
<td>Stratus</td>
<td>0-2</td>
</tr>
<tr>
<td>5</td>
<td>Stratocumulus</td>
<td>0-2</td>
</tr>
<tr>
<td>6</td>
<td>Cumulus</td>
<td>1-8</td>
</tr>
<tr>
<td>7</td>
<td>deep convection</td>
<td>1-8</td>
</tr>
<tr>
<td>8</td>
<td>Nimbostratus</td>
<td>1-8</td>
</tr>
</tbody>
</table>

Table 1: The classification of clouds by Cloud\_Scenario.

4 Results

The comparison of reanalysis data records and satellite data showed in all cases, that the reanalyses ERA-Interim and MACC overestimate the cloud cover. In Figure 5 it is exhibited, that north of 60° the cloud cover of the reanalyses is greater than the cloud cover measured by DARDAR. As well it is shown in figure 5, that the annual cloud cycle is not well approximated by the reanalyses data. The expected winter minimum of the cloud cover in February/March, which is visible in the satellite data (green) is not apparent in either reanalysis data records MACC (red) or ERA-Interim (blue).
Figure 5: Cloud cover in percent over the Arctic by MACC (red), ERA-Interim (blue) and DARDAR (green) for the years 2007 till 2010.

The reanalyses data demonstrate a cloud cover minimum in summer. The average value of the time period 2007 till 2010, in figure 5(e), present, that the reanalysis data records go similar to each other and converge from August onward. Also both reach their annual maximum in October, which agrees with the satellite observation.

In the figures 6 and 7 it is clearly visible that the calculated cloud cover by ERA-Interim and MACC do not depend on the observed cloud cover by the satellites. This
Figure 6: Correlation between the daily averages of the cloud cover of DARDAR and ERA-Interim over different surface conditions, for the time period 2007 till 2010 with the linear regression. On top in the middle is the p-value of the Pearson’s r-test.

Figure 7: Correlation between the daily averages of the cloud cover of DARDAR and MACC over different surface conditions, for the time period 2007 till 2010 with the linear regression. On top in the middle is the p-value of the Pearson’s r-test.

was also shown by Zygmuntowska et al. (2012). The corresponding measurements are strongly spread. Even when the satellite detect a cloud free condition, the cloud cover by ERA-Interim is on average 60% and by MACC 67% (compare figures 6(a) - 7(c)). The regression lines emphasize this fact. Also it is discernible, that a higher DARDAR cloud cover is corresponding with an increased ERA-Interim cloud cover (compare figure 6). The same applies to the MACC’s cloud cover in figure 7. In both data records, the correlation coefficient is smallest in the ice case and highest in the ice edge case (compare Table 2). The ERA-Interim correlation values are 0.08 - 0.12 higher than the MACC’s correlation coefficients. For the statistical significance of the correlation
Table 2: 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.

<table>
<thead>
<tr>
<th></th>
<th>MACC</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ocean</td>
<td>0.28719</td>
<td>0.08248</td>
<td>0.21181</td>
<td>0.4044</td>
<td>0.16354</td>
<td>0.28422</td>
</tr>
<tr>
<td>ice</td>
<td>0.24523</td>
<td>0.06024</td>
<td>0.14998</td>
<td>0.32362</td>
<td>0.10473</td>
<td>0.19275</td>
</tr>
<tr>
<td>edge</td>
<td>0.31474</td>
<td>0.09906</td>
<td>0.21776</td>
<td>0.40888</td>
<td>0.16719</td>
<td>0.27807</td>
</tr>
</tbody>
</table>

The Pearson’s $r$ test was used, which assumes as null hypothesis that two variables are independent. 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%. In the figures 9 and 10 it is exhibited the monthly average of the cloud cover for the time period 2007 till 2010 by the reanalyses data records. Like mentioned above neither the data of 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.
5 Conclusion and Outlook

In this work, a comparison between the cloud cover from 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 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 (compare figures 6 and 7) is weak.

In summary it is plainly visible, that neither ERA-Interim’s cloud cover nor MACC’s cloud cover basically mirror the observed cloud cover by satellites in the Arctic. Also these data are not convincing regarding that there is a 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) said that clouds with a cloud top height lower than 3 km play the largest part in the Arctic energy budget. In this thesis 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 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. If this is the case, it is possible to estimate the feedback between sea ice and clouds.
Figure 8: The annual variability of the sea ice concentration by ERA-Interim.
Appendix B  ERA-Interim annual cloud cycle

Figure 9: cloud cover average of the years 2007 till 2010 by ERA-Interim.
Appendix C  MACC annual cloud cycle

Figure 10: cloud cover average of the years 2007 till 2010 by MACC.
References


REFERENCES


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