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Arctic clouds and surface radiation – a critical comparison of satellite retrievals and the ERA-interim reanalysis

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Abstract

Clouds regulate Earth's radiation budget, both by reflecting part of the incoming sunlight leading to cooling and by absorbing and emitting infrared radiation which tends to have a warming effect. Globally averaged, at the top of the atmosphere the cloud radiative effect is to cool the climate, while at the Arctic surface, clouds are thought to be warming. Ground-based observations of central Arctic Ocean cloudiness are limited to sporadic field campaigns. Therefore many studies rely on satellite- or reanalysis data. Here we compare a passive instrument, the AVHRR-based retrieval from CM-SAF, with recently launched active instruments onboard CloudSat and CALIPSO and the widely used ERA-Interim reanalysis. We find that the three data sets differ significantly. In summer, the two satellite products agree having monthly means of 70–80 percent, but the reanalysis are approximately ten percent higher. In winter passive satellite instruments have serious difficulties, detecting only half the cloudiness of the reanalysis, active instruments being in between. The monthly mean long- and shortwave components of the surface cloud radiative effect obtained from the ERA-Interim reanalysis are about twice that calculated on the basis of CloudSat retrievals. We discuss these discrepancies in terms of instrument-, retrieval- and reanalysis characteristics.

1 Introduction

The Earth's climate is observed to change since the beginning of the 20th century. This climate change is more pronounced in the high latitude Arctic region than in the rest of the world (ACIA, 2005; Serreze and Francis, 2006; Solomon et al., 2007). This Arctic amplification of climate change can be identified by rising surface temperatures and by the rapid decline of the Arctic sea ice extent, which have been attributed to anthropogenic greenhouse gas forcing (Gillett et al., 2008; Min et al., 2008). However, it is generally recognized that considerable natural variability prevails in the Arctic (Serreze et al., 2007). The sea ice decline culminated in 2007 when the Arctic sea ice reached

ACPD
11, 31495–31522, 2011

a September minimum extent of 4.3×10^6 km^2 – a value more than forty percent below that at the beginning of the satellite-era in 1979 (Stroeve et al., 2007). The underlying mechanisms making the Arctic climate both more sensitive and variable than the rest of the globe are not well understood. Suggestions include regionally enhanced warming mechanisms, including the surface albedo changes arising from melting snow and ice in a warming climate (Manabe and Wetherald, 1975), water vapor (Manabe and Wetherald, 1980), the vertical stratification trapping heat near the surface (Manabe and Wetherald, 1975; Held, 1979), along with shifts in the atmosphere and ocean circulations leading to more transport of heat and moisture into the Arctic (Manabe and Wetherald, 1975; Holland and Bitz, 2003; Graversen et al., 2008).

Clouds play a central, yet complex role in the Arctic climate system. Clouds both cool by reflecting incoming sunlight back to space, and warm by absorbing outgoing infrared radiation and typically emit at a lower temperature than the surface. We define the cloud radiative effect (CRE) as the difference between the actual net radiative fluxes and what they would have been in an otherwise identical, but cloud-free atmosphere. Globally, at the top of the atmosphere clouds cool the Earth system (Schneider, 1972; Ramanathan et al., 1989), whereas clouds have a predominantly warming effect at the surface in the Arctic (Walsh and Chapman, 1998; Intrieri et al., 2002a). In the Arctic, the dry background atmosphere enhances the cloud longwave warming effect, while the high surface albedo over snow and ice combined with the high solar zenith angles acts to reduce the cloud shortwave cooling effect (Curry and Herman, 1985; Curry et al., 1996). The semi-permanent Arctic inversion (Kahl et al., 1996) further complicates estimates of the longwave radiative effect because the cloud might occasionally be warmer than the surface. The spread in cloud fields in global climate models is large, including the phase of the annual cycle of total cloud cover, with monthly means ranging from 35 to 95 percent, vertically integrated liquid water paths varying by more than an order of magnitude and widely disparate cloud radiative effects, for example varying from $-30\,\mathrm{W\,m^{-2}}$ to $+10\,\mathrm{W\,m^{-2}}$ in summer months (Karlsson and Svensson, 2011).

ACPD
11, 31495–31522, 2011

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Early studies suggested that clouds add to Arctic climate sensitivity and variability by constituting a regionally positive feedback mechanism through enhanced cloudiness in a warming climate (Schneider, 1972; Ramanathan, 1977; Wetherald and Manabe, 1988). However, the many possible interactions of clouds with the underlying surface seriously complicate these estimates, as observations and models suggest increased cloudiness as a response to sea-ice loss (Abbot et al., 2009; Kay and Gettelman, 2009; Cuzzone and Vavrus, 2011; Vavrus et al., 2011), which may lead to either cooling or warming due to the decreased surface albedo and depending on seasonality. Additionally, several studies indicate that aerosol influences on cloud emissivity are particularly strong in the Arctic, leading to aerosol indirect effects which are regionally warming, as opposed to the global cooling effect (Garrett and Zhao, 2006; Lubin and Vogelmann, 2006; Mauritsen et al., 2011). To better understand the cloud radiative effect, cloud climate feedbacks and the cloud-sea-ice interactions, it is necessary to have precise information about not only cloud properties and occurrence, but also the environment in which they are embedded.

Clouds are flimsy objects with poorly defined boundaries, partly because they consist of droplets and ice particles dispersed in a turbulent media, partly because of their ability to form and evaporate depending on the local super- or subsaturation. It is difficult to tell where they begin and where they end, and therefore we rather tend to define them in terms of their radiative properties. For example, the human observer will require them to be visible; detectable by the human eye under prevailing light conditions. Remote sensors may use certain characteristics of visible and infrared emission, while lidars and radars operationally define thresholds in the detected returned signal. Naturally, the results will depend on the characteristics of the sensor, the cloud detection threshold combined with the targeted cloud itself.

The Arctic is known to be a highly cloudy region. Over the Arctic Ocean, mid- and high-level clouds are believed to be mainly associated with frontal systems and they vary seasonally in amount (Curry and Herman, 1985). In a stable atmosphere, which is prevalent in the central Arctic, clouds can form when relatively warm and moist air is advected into the polar regions. Over the cooler surface the air cools and condensation occurs to form stratus or stratocumulus clouds (Herman and Goody, 1976; Curry, 1983). This type of clouds tend to be shallow, from a few hundred meters up to one to two kilometers. Under unstable atmospheric conditions low-level cumulus clouds can form when air is advected over relatively warm surfaces. In wintertime this can be observed over open leads, or cracks in the sea ice, and throughout the year during cold-air outbreaks from the pack-ice to the open ocean (Curry et al., 1996). Clouds tend to extend deeper under unstable conditions.

Previous studies based on passive sensors and human observers found a total cloud cover of up to 90–95 percent in summer months and values around 50 percent in winter, with sharp transition seasons in April and October (Huschke, 1969; Schweiger and Key, 1992; Eastman and Warren, 2010). The total cloud cover was found to be mainly dominated by semi-permanent low-level clouds, while mid- and high-level clouds show a low amplitude in the annual cycle. However, since these previous studies have relied on either human observations, or passive satellite instruments it remains an open question to which extent wintertime cloud observations and the observed annual cycle in cloudiness is caused by the lack of sunlight in winter causing a poor detection of clouds, confirmed by active sensors showing around 70 percent cover in winter (Intrieri et al., 2002a). Further, clouds in the Arctic are frequently optically thin (Shupe and Intrieri, 2004; Sedlar et al., 2010), occasionally sub-visible due to the lack of aerosol upon which cloud droplets can form, making detection by any means particularly difficult even in summer (Mauritsen et al., 2011).

The scientific community therefore had high expectations on improving the situation when NASA launched two new active satellites in 2007, carrying a millimeter wavelength cloud radar, CloudSat, and a dual-channel lidar, CALIPSO (Stephens et al., 2002). These active sensors are less sensitive to environmental conditions, promise low detection limits, and require fewer assumptions in the retrievals of cloud properties, than do passive instruments. However, even these instruments do have their limitations, as CloudSat is unable to detect optically thin clouds and retrievals are hampered

ACPD
11, 31495–31522, 2011

by ground clutter at levels near the surface, while CALIPSO is attenuated if exposed to scenes with optically thick clouds.

In this study the main focus is to advance knowledge of cloud occurrence in the Arctic on the basis of new datasets, and further to study cloud impacts on the surface radiation budget over the Arctic Ocean. We evaluate climatologies based on CloudSat and CALIPSO, new retrievals from passive instrument AVHRR satellites and from the ERA-Interim reanalysis. The components of the cloud radiative effect estimated from CloudSat and ERA-Interim are compared. Ground-based observations from the SHEBA project (1997–1998) are used to estimate the possible impacts of instrumental shortcomings and reanalysis biases on the results.

2 Data and methods

In this study the Arctic is defined as the area north of 68° N, excluding the area between 30° E and 100° W south of 75° N as it is not representative for central Arctic Ocean conditions (Fig. 1). We interpolate and aggregate all our statistical quantities to a common polar stereographic grid with a resolution of 200 km to facilitate the intercomparison. The grid resolution was chosen to minimize sampling noise, while retaining spatial information. Only data over the oceans and sea ice are analyzed.

CloudSat and CALIPSO were launched in June 2007 and fly in a tight orbital coordination so that they image the same atmospheric volume within short time. CloudSat is carrying the Cloud Profiling Radar (CPR) and CALIPSO is carrying the Cloud-Aerosol-Lidar with Orthogonal Polarization (CALIOP). The wavelength of the radar pulse is 3 mm and the small Rayleigh cross section allows the pulse to penetrate deep into the atmosphere and detect multiple layers of clouds. The Cloud-Aerosol-Lidar in turn with wavelengths of 532 nm and 1064 nm is able to detect clouds which are thin and dominated by small particles. Both instruments are active sensors, measuring the energy backscattered from the clouds, and therefore, in contrast to passive retrievals, cloud detection is not affected by the frequent temperature inversions and difficult light

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
ACPD
11, 31495–31522, 2011
Arctic clouds and radiation
M. Zygmuntowska et al.

conditions in the Arctic region. Nonetheless it is a known issue that clouds at low altitudes below 1000 m are often not identified and below 500 m almost no clouds are detected. Here the radar signal is contaminated by surface clutter from the reflected radar beam, while the lidar pulse is frequently attenuated by thick overlaying clouds (Mace, 2003; Winker et al., 2007; Stephens et al., 2008).

A combined Radar-lidar cloud mask has been obtained from the 2B-GEOPROF-LIDAR data set. The 2B-GEOPROF-LIDAR data set is a level 2 product, which combines information from CloudSat and CALIPSO level 1 data sets and auxiliary data to retrieve information about cloud occurrence (Mace, 2008). Auxiliary data is obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) and contains state variables such as pressure, temperature, and humidity (Partain, 2004). MODIS auxiliary data provides radiance and cloud mask data from the MODIS satellite that overlap each CloudSat CPR footprint (Partain, 2004). The merged 2B-GEOPROF-LIDAR data set provides a hydrometeor fraction for every vertical level and up to five cloud tops and bases for every profile. In the present study, information about cloud tops are used to calculate a combined cloud mask which has been interpolated to the common polar stereographic grid. Low level clouds are defined as clouds with a cloud top below 3000 m. To analyze the influence of clouds on the radiation budget, the 2B-FLXHR data set is used, another level 2 Standard Data Product provided by CloudSat (L'Ecuyer, 2007; L'Ecuyer et al., 2008). It provides down- and upwelling radiative flux estimates for every profile. Calculations are based on atmospheric transmittance and reflectivity from CloudSat, and information about humidity and temperature are obtained from the ERA-Interim reanalysis (see below). No information from CALIPSO is used when calculating fluxes.

Over the Arctic region the 2B-FLXHR dataset is biased as no information about the surface albedo alterations due to sea ice has been included. Instead the albedo is assumed to equal that of an open ocean. To be able to use this dataset, values for upwelling fluxes are recalculated in the present study. Based on retrievals for sea ice concentration from the SSM/I (Kaleschke et al., 2001) the albedo of all grid cells with

ACPD
11, 31495–31522, 2011

a concentration of sea ice above 15 percent is set to a value of 45 and 75 percent, respectively, to get an estimate of the upper and lower bounds of net radiative short-wave fluxes. Changes in surface long-wave fluxes from the ocean as well as multiple scattering between the bright sea ice surface and clouds are not accounted for.

The Advanced Very High Resolution Radiometer (AVHRR) measures the irradiance from the Earth in 6 spectral bands from visible (≈0.58 µm) to far-infrared (≈12.5 µm), and has been in use since the 1970s providing some potential for studying longterm changes. Here data processed by EUMETSAT's Satellite Application Facility on Climate Monitoring (CM-SAF) has been used. Monthly averaged values for the fractional cloud cover are analyzed what can be seen as the percentage of cloud contaminated pixels (Kaspar et al., 2009). Values are provided on a Lagrangian grid with a spatial resolution of 15 km × 15 km and have here been interpolated to the common polar stereographic grid. Unfortunately, at the time of writing there are big gaps in the data set, hence data for the Arctic region is only available from November 2007 to April 2008 and for 2009.

ERA-Interim is a re-analysis of meteorological observations produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Simmons et al., 2006). As in weather-forecast models, data assimilation comprises a sequence of analysis steps in which modeled background information for a short period is combined with observations to produce an optimal estimate of the state of the atmosphere at a particular time. In ERA-Interim clouds are modeled quantities which are only indirectly constrained by the available observations of temperature, humidity etc.

To gain further insights into the cloud occurrence over the Arctic Ocean we use ground-based lidar and radar observations from the Surface Heat Budget of the Arctic Ocean project (SHEBA) (Uttal et al., 2002). The SHEBA field campaign took place from 1997 to 1998, and was aimed at understanding the ocean-ice-atmosphere coupling in the Arctic. The measurements were carried out on a floating ice sheet in the Beaufort Sea between 70° N and 80° N and 140° W and 170° W. Monthly mean cloud fraction has been calculated from a 10-min averaged combined dataset (Intrieri et al., 2002b). We

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
11, 31495–31522, 2011

Arctic clouds and radiation

M. Zygmuntowska et al.

here emphasize that this is slightly different from the usual definition of cloud fraction. The percentage of 10 min time intervals within one month when either the lidar, or radar, observed a cloud is likely to provide an overestimate of cloud fraction, although this is a minor issue for stratiform clouds.

3 Arctic cloud cover

The yearly cycles of monthly mean total and low-level cloud fraction over the Arctic Ocean from the three datasets are shown in Fig. 2. In summer months, from May until September, the passive and active satellite instrument cloud fraction estimates agree surprisingly well, with slightly (5–10 %) lower cloud fractions retrieved by AVHRR. Both retrievals show a relative minimum of cloudiness in July. They both exhibit a seasonal cycle with more cloudiness in summer and autumn, relative to winter and early spring. In the polar winter, however, the passive satellites detect far less clouds than the active satellites, down to half the cloud fraction in the midst of winter in December and January. ERA-Interim exhibits a relatively weak annual cycle, with a minimum in June, and values varying between 80 and 95 percent total cloud cover. The low-level clouds differ even more between ERA-Interim and the active satellite estimate, with nearly two times the cloud fraction in the reanalysis. In ERA-Interim, the variability in low-level clouds seems to dominate the – small – seasonal cycle in total cloudiness. This is only to some extent found for the CloudSat/CALIPSO retrievals. In these, the maxima in May and October, and the local minimum in July, are obviously due to the low-level cloudiness, but the general increase from winter to autumn, and decrease thereafter, is not seen in the low-level cloudiness. Year-to-year variability within the individual datasets is surprisingly small, giving us some hope that the short records available provide useful climatological information, while understanding the underlying causes for the large discrepancies between the datasets seems crucial.

The geographical cloud fraction distributions for the year 2009 in the three datasets reveal further points of systematic agreement and differences (Fig. 3). Arguably, the

ACPD
11, 31495–31522, 2011

best agreement between the datasets across all seasons is found over the open ocean in the North Atlantic, where all datasets show 80–90 percent cloud fraction with only weak seasonal cycles. In the summer season when the datasets agree best overall, there is a tendency for ERA-Interim to show more clouds over the sea ice in the Beaufort Sea, while Cloudsat/CALIPSO systematically detects the most clouds over land of the three. In the North Atlantic sector during the coldest seasons, winter and spring, CloudSat/CALIPSO shows significantly less clouds over sea ice than open ocean, while ERA-Interim exhibits slightly more cloudiness over sea ice relative to the open ocean.

The strong seasonal cycle in cloud fraction over the Arctic Ocean observed with the passive instrument AVHRR might be due to the lack of sunlight in the Arctic winter, effectively disabling the visible channels. Another problem could be the strengthening of the Arctic temperature inversion in the cold seasons, making it difficult to distinguish a cloud from the surface in the infra-red spectrum. The resulting biases depends on details of the algorithm used in the satellite retrieval. Evidence for these notions is found in the poleward decrease in cloud fraction in winter, spring and autumn, which is not supported by the other datasets. We cannot tell from our analysis which effect has the largest impact, however it seems very likely that the seasonal cycle observed with passive instruments is exaggerated.

Ground-based longterm cloud observations with active instruments, such as ceilometers, cloud radars and lidars, are sparse over the Arctic Ocean and is essentially limited to the SHEBA campaign from 1997 to 1998 (Intrieri et al., 2002a). Thus direct comparison with the active satellites is unfortunately presently not possible, since they were not launched at that time. However, we can compare with ERA-Interim (Fig. 4). The agreement between observed cloud fraction and the reanalysis is striking, however, there are at least two caveats to this result. First, the definition of cloud fraction used in the merged radar and lidar dataset is that it is cloudy if either instrument detects a cloud in a 10-min interval. Arguably, this approach is going to inflate the result to some extent, though possibly only by a small amount in the Arctic setting

ACPD
11, 31495–31522, 2011

which is dominated by stratus and stratocumulus clouds. The reanalysis assimilated radiosoundings carried out during SHEBA, which could potentially help ERA-Interim produce a reasonable cloud cover over the region. To shed some light on the latter, we plot monthly mean cloud fractions from ten other individual years from the reanalysis. For the SHEBA-year ERA-Interim is significantly outside the multi-year ensemble only in March, and, if anything the observed summer cloud cover is about 5 percent higher than the multi-year mean from the reanalysis. These results certainly do not help explain the difference between ERA-Interim and CloudSat/CALIPSO.

The Arctic skies are largely dominated by clouds in the lowest kilometer (Intrieri et al., 2002a), and these low-level clouds dominate the surface radiation budget (Shupe and Intrieri, 2004). Yet, CloudSat detects no clouds below 500 m and has only limited detection between 500 and 1000 m. It is therefore of particular interest to study how these limitations potentially affect the cloud fraction estimates based on that particular instrument. We utilize the SHEBA observations to estimate the effect, by artificially removing clouds detected below these limits and then evaluate the total cloud fraction (Fig. 4). The effect depends on season and limit, where removing all clouds below 500 m results in a deficit peaking at about 20 percent in winter months and around 10 percent in other months. When neglecting all clouds below 1000 m, the deficit total cloud fraction increases further. The overall results of this sensitivity analysis does not change significantly when only considering low-level clouds below 3000 m (not shown).

It remains uncertain to which extent CALIPSO helps in correcting this serious limitation of CloudSat in detecting low-level clouds when the two datasets are merged in the 2B-GEOPROF-LIDAR product to retrieve the cloud fractions shown in Figs. 2 and 3. However, it seems reasonable to assume that the lidar is adding to the total cloud fraction. Therefore, we cannot fully reconcile the differences between ERA-Interim and CloudSat/CALIPSO. Below we shall further discuss the cloud radiative effect estimates, which is currently only based on CloudSat, and hence neglects the lowest clouds.

ACPD
11, 31495–31522, 2011

4 Arctic cloud radiative effect

Monthly means of the long- and shortwave components of the surface cloud radiative effect (CRE) from CloudSat and ERA-Interim are shown in Fig. 5. Data are again averaged over the Arctic Ocean as indicated in Fig. 1. The reader is reminded that the satellite estimates of CRE are based on CloudSat only as described in Sect. 2, and that the shortwave component of CRE has been compensated here for the erroneous use of open ocean surface albedo where ice is present.

Shortwave CRE has a distinct annual cycle being near-zero in the polar-night winter and peaking in late summer in July or August when solar input is still high and sea-ice cover close to minimum. The strength in the cycle from CloudSat depends strongly on the assumed surface albedo in spring and summer as indicated by the red shading. ERA-Interim shortwave CRE agrees with CloudSat, except in July and August when the reanalysis exhibits about twice the shortwave CRE of the satellite estimate, and to some extent September with still lower values in the satellite estimate. The reanalysis uses its own surface albedo, which on average is lower than the assumed values used for CloudSat, even for the lower bound estimate. Compensating the reanalysis shortwave CRE in an analogous way to the satellite, however, only reduces shortwave CRE to about 100 Wm^{-2} in both July and August (not shown), and it is therefore not sufficient to explain the difference.

In addition to depending on the surface albedo, shortwave CRE depends on a number of other factors, such as cloud fraction, cloud liquid water path, cloud droplet effective radius, horizontal homogeneity of the clouds, and to a lesser extent on the presence of mixed-phase or ice clouds, the Arctic background aerosol and variations in other atmospheric shortwave absorbers. Figure 6 shows a comparison of ERA-Interim average liquid water path with that observed during the SHEBA campaign using a dual-channel microwave radiometer. Interestingly, the reanalysis exhibits only around half the observed liquid water path. As we have seen before, ERA-Interim cloud cover is about the same as observed, meaning that clouds in the reanalysis are thinner than

ACPD
11, 31495–31522, 2011

indicated by the observations, which can then be ruled out as a cause for the stronger shortwave CRE in ERA-Interim relative to the CloudSat estimate.

Longwave CRE differ throughout the year between CloudSat and ERA-Interim by about a factor two or more, the reanalysis exhibiting the larger values. The largest discrepancies are found in summer and early autumn. Longwave CRE at the surface depends on cloud cover, thickness, liquid droplet radius and the presence and properties of cloud ice particles, together determining their emissivity, combined with cloud height and temperature, and the background atmosphere profiles of temperature, water vapor, aerosol and greenhouse gases, together determining the radiative contrast between clear and cloudy skies.

Figure 7 compares the vertically integrated water vapor path between ERA-Interim and observations obtained from the dual-channel microwave radiometer and radiosoundings performed during the SHEBA campaign. The two measurements are found to be in very good agreement, providing reliable information about the water vapor in the atmosphere. Comparison to reanalysis shows a reasonable agreement in winter and spring, while in summer the reanalysis atmosphere is much drier than observed. This could explain why the longwave CRE in ERA-Interim is so strong during summer, relative to SHEBA estimates. It does not, however, explain the difference between CloudSat and ERA-Interim, because the CloudSat derived CRE is based on the very same temperature and humidity profiles from ERA-Interim.

The available evidence is consistent with the missing low-level clouds by CloudSat explaining part of the discrepancies in CRE to ERA-Interim, as these clouds tend to be optically thick and warm (Shupe and Intrieri, 2004). Estimates of short- and longwave CRE from observations obtained during the SHEBA campaign are generally in between the two, albeit closer to CloudSat (Intrieri et al., 2002a). Here one needs to keep in mind that SHEBA was representative of a single ice-floe, whereas our results are averaged over the entire Arctic Ocean combining both ice and open ocean. Hence, one would expect the true area-averaged shortwave CRE to be higher than the SHEBA-based estimates, lending at least some credibility to ERA-Interim. It is

ACPD
11, 31495–31522, 2011

understandable that ERA-Interim has a stronger longwave CRE in summer relative to SHEBA-based estimates because the reanalysis has a large dry-bias. However, the CloudSat-based longwave CRE estimates also use the ERA-Interim temperature and water vapor profiles, narrowing the source of discrepancy to the CloudSat clouds and assumptions on their emissivity.

5 Summary and conclusions

Clouds play a central role in regulating the energy balance of the Earth, and because they are so heterogeneous, regionally they help determine the character of weather and climate. At the Arctic surface they tend to be warming most of the year, shifting the surface heat budget up by 10 to 50 $\mathrm{W\,m^{-2}}$ from autumn until spring, while in summer they tend to be slightly cooling the surface. The warming property of Arctic clouds is due to a combination of them existing in a dry and cold environment together with a highly reflective surface and a weak solar input. The role of clouds in Arctic climate change is largely unknown. Yet, we know so little about something as basic as their abundance; the disagreement in the seasonal cycle and geographical distribution among the three datasets we analyzed is striking:

1. Our results show that even state-of-the-art active satellite instruments have trouble in the Arctic environment. For example, CloudSat and CALIPSO have problems detecting the low-level cloud cover in the first 500–1000 m. Ground-based measurements, using similar radars and lidars however pointed upwards, show higher total cloudiness and reveals the dominance of low-level clouds in the central Arctic Ocean (Intrieri et al., 2002b), which is not captured by the satellite borne instruments.

2. In summer passive instrument CM-SAF satellite retrievals agree surprisingly well with the active instruments, with cloud fractions slightly lower by 5–10 %. In late

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

11, 31495–31522, 2011

autumn until early spring, when the sun is below the horizon most of the time, retrievals based on passive instrument AVHRR satellites clearly fail to detect clouds. This is evident from the seasonal cycle and the apparently artificial southward gradient of cloud fraction over sea-ice in autumn and spring. The under-detection of the passive satellite retrievals is not too surprising as some of the used spectral channels are in the visible range, hampered by the lack of sunlight, while the infrared retrievals is difficult due to the semi-persistent Arctic temperature inversion.

3. The total cloud cover produced by the ERA-Interim reanalysis model agrees surprisingly well in direct comparison to the SHEBA observation. One could suspect that the reanalysis was aided by observations from radiosondes launched during the SHEBA campaign which were likely assimilated into ERA-Interim. However, the SHEBA-year was found to be insignificantly different from other years in the reanalysis, and if anything the observed cloud cover during SHEBA is slightly above ERA-Interim.

Surface cloud radiative effects (CRE) estimated from CloudSat (not including CALIPSO) and ERA-Interim disagrees roughly by a factor two in the individual longwave and shortwave components, while in the net these differences tend compensate to some extent during summer months. Cloud radiative effect estimates depend on a large number of quantities and assumptions concerning properties of both the clouds themselves and their environment. While the active instrument CloudSat derived estimate – after compensation for the clearly erroneous surface albedo assumption of open water everywhere – appears to be closer to previous estimates from the SHEBA campaign than is ERA-Interim, this may well be a fortuitous result of compensating errors and lack of representability of the SHEBA observations:

1. We show that ERA-Interim has a strong dry-bias in summer having only slightly more than half the observed vertically integrated water vapor path than SHEBA. This bias would favor a stronger longwave CRE because the contrast between cloudy and clear skies is enhanced in the infrared, and indeed ERA-Interim shows

ACPD
11, 31495–31522, 2011

stronger summer longwave CRE than previously observed (Intrieri et al., 2002b; Sedlar et al., 2010). However, the CloudSat estimates of longwave CRE use the ERA-Interim temperature and humidity profiles meaning that difference must be due to CloudSat detecting too few and/or too optically thin clouds.

2. While the shortwave CRE observed during SHEBA is between, but closer to CloudSat than ERA-Interim, it seems plausible that the Arctic Ocean area-average shortwave CRE over a mixture of ice and open water should be larger than the estimate from SHEBA which was on an ice-floe.

In both cases the results are consistent with the fact that CloudSat cannot detect clouds below 500 m, although one cannot rule out influences from assumptions made on cloud optical properties in both datasets.

The presented results have important implications for studies of trends and interactions among clouds and Arctic climate. The products we have presented are three popular choices among many available for this purpose, and they all have their strengths and weaknesses. Clearly, passive instrument based retrievals serve only limited purpose in anything but summer months, while they do offer by far the longest satellite records. Recent studies indicate, however, that trends derived from some of these retrievals are suspicious (Eastman and Warren, 2010). CloudSats inability to detect low-level clouds is particularly problematic in the Arctic, as most of the clouds occur very close to the surface, and it may well bias studies if for example synoptic scale motion (subsidence or convergence) or the varying lower boundary conditions (ice or open ocean) favors one cloud regime over another leading to spurious results (Cuzzone and Vavrus, 2011). On the other hand, these active satellite instruments offer unprecedented capabilities to observe many aspects of clouds, in particular during the polar night. Finally, the reanalyses are attractive in that they offer a complete and long-term dataset, incorporating practically all available conventional observations. Yet, they often suffer from considerable biases and spurious jumps associated with changes in the observational system, and maybe most important: their clouds are entirely modeled entities, which are only indirectly constrained by observations. Nevertheless, the ERA-Interim cloud and radiation properties are the most plausible by our results.

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References

Abbot, D. S., Walker, C. C., and Tziperman, E.: Can a convective cloud feedback help to eliminate winter sea ice at high CO_2 concentrations?, J. Clim., 22, 5719–5731, 2009. 31498

Arctic Climate Impact Assessment (ACIA), Cambridge University Press, 1042 pp., 2005. 31496

Curry, J. A.: On the formation of continental polar air, J. Atmos. Sci., 40, 2279–2292, 1983. 31499

Curry, J. A. and Herman, G. F.: Infrared radiative properties of Arctic stratus clouds, J. Clim. Appl. Meteorol., 24, 525–538, 1985. 31497, 31498

Curry, J. A., Rossow, W. B., Randall, D., and Schramm, J. L.: Overview of Arctic cloud and radiation characteristics, J. Clim., 9, 1731–1763, 1996. 31497, 31499

Cuzzone, J. and Vavrus, S.: The relationships between Arctic sea ice and cloud-related variables in the ERA-Interim reanalysis and CCSM3, Environ. Res. Lett., 6, 014016, 2011. 31498, 31510

ACPD

11, 31495–31522, 2011

Arctic clouds and radiation

M. Zygmuntowska et al.

Eastman, R. and Warren, S. G.: Arctic cloud changes from surface and satellite observations, J. Clim., 23, 4233–4242, 2010. 31499, 31510
Garrett, T. J. and Zhao, C.: Increased Arctic cloud longwave emmisivity associated with pollution from mid-latitudes, Nature, 440, 787–789, 2006. 31498
Gillett, N. P., Stone, D. A., Stott, P. A., Nozawa, T., Karpechko, A. Y., Hegerl, G. C., Wehner, M. F., and Jones, P. D. Attribution of polar warming to human influence, Nat. Geosci., 1, 750–754, 2008. 31496
Graversen, R. G., Mauritsen, T., Tjernström, M., Källén, E., and Svensson, G.: Vertical structure of recent Arctic warming, Nature, 451, 53–56, 2008. 31497
Held, I. M.: The tropospheric lapse rate and climate sensitivity: Experiments with a two-layer atmospheric model, J. Atmos. Sci., 35, 2083–2098, 1979. 31497
Herman, G. F. and Goody, R.: Formation and persistence of summertime Arctic stratus clouds, J. Atmos. Sci., 33, 1537–1553, 1976. 31499
Holland, M. M. and Bitz, C. M.: Polar amplification of climate change in coupled models, Clim. Dyn. 21, 221–232, 2003. 31497
Huschke, R. E.: Arctic cloud statistics from "Air-Calibrated" surface weather observations, Rand Corp. Memo., RM-6173-PR, Santa Monica, California, 79 pp., 1969. 31499
Intrieri, J. M., Fairall, C. W., Shupe, M. D., Persson, P. O. G., Andreas, E. L., Guest, P. S., and Moritz, R. E.: An annual cycle of Arctic surface cloud forcing at SHEBA, J. Geophys. Res., 107, C10, doi:10.1029/2000JC000439, 2002a. 31497, 31499, 31504, 31505, 31507
Intrieri, J. M., Shupe, M. D., Uttal, T., and McCarthy, B. J.: An annual cycle of Arctic cloud characteristics observed by radar and lidar at SHEBA, J. Geophys. Res. 107, C10, doi:10.1029/2000JC000423, 2002b. 31502, 31510
Kahl, J. D. W., Martinez, D. A., and Zaitseva, N. A.: Long-term variability in the low-level inversion layer over the Arctic Ocean, Int. J. Clim., 16, 1297–1313, 1996. 31497
Kaleschke, L., Lüpkes, C., Vihma, T., Haarpaintner, J., Bochert, A., Hartmann, J., and Heygster, G.: SSM/I sea ice remote sensing for mesoscale ocean-atmosphere interaction analysis, Can. J. Remote Sens. 27, 526–537, 2001. 31501
Karlsson, J. and Svensson, G.: The simulation of Arctic clouds and their influence on winter surface temperature in present-day climate in the CMIP3 multi-model dataset, Clim. Dyn., 36, 623–635, doi:10.1007/s00382-010-0758-6, 2011. 31497
Kaspar, F., Hollmann, R., Lockhoff, M., Karlsson, K.-G., Dybbroe, A., Fuchs, P., Selbach, N., Stein, D., and Schulz, J.: Operational generation of AVHRR-based cloud products for Europe

ACPD
11, 31495–31522, 2011

and the Arctic at EUMETSATs Satellite Application Facility on Climate Monitoring (CM-SAF), Adv. Sci. Res. 3, 45–51, 2009. 31502

Kay, J. E. and Gettelman, A.: Cloud influence on and response to seasonal Arctic sea ice loss, J. Geophys. Res., 114, D18204, doi:10.1029/2009JD011773, 2009. 31498

L'Ecuyer, T. S.: Level 2 Fluxes and Heating Rates Product, Process Description and Interface Control Document, Version 5.1. Cooperative Institute for Research in the Atmosphere, Colorado State University, available at: http://cloudsat.cira.colostate.edu/ICD/2B-FLXHR/2B-FLXHR_PDICD_5.1.pdf, 2007. 31501

L'Ecuyer, T. S., Wood, N. B., Haladay, T., Stephens, G. L., and Stackhouse, P. W.: Impact of clouds on atmospheric heating based on the R04 CloudSat fluxes and heating rates data set, J. Geophys. Res., 113, D00A15, doi:10.1029/2008JD009951, 2008. 31501

Lubin, D. and Vogelmann, A. M.: A climatologically significant aerosol longwave indirect effect in the Arctic, Nature, 439, 453–456, 2006. 31498

Mace, G.: Level 2 Radar-Lidar Geoprof Product, Process Description and Interface Control Document, Version 0 – Draft. California Institute of Technology, Pasadena, California, 2003. 31501

Mace, G.: A NASA Earth System Science Pathfinder Mission, CloudSat Standard data Products Handbook. Cooperative Institute for Research in the Atmosphere, Colorado State University, 2008. 31501

Manabe, S. and Wetherald, R. T. The effects of doubling the CO_2 concentration on the climate of a general circulation model, J. Atmos. Sci., 32, 3–15, 1975. 31497

Manabe, S. and Wetherald, R. T.: On the distribution of climate change resulting from an increase in CO_2 content of the atmosphere, J. Atmos. Sci., 37, 99–118, 1980. 31497

Mauritsen, T., Sedlar, J., Tjernström, M., Leck, C., Martin, M., Shupe, M., Sjogren, S., Sierau, B., Persson, P. O. G., Brooks, I. M., and Swietlicki, E.: An Arctic CCN-limited cloud-aerosol regime, Atmos. Chem. Phys., 11, 165–173, doi:10.5194/acp-11-165-2011, 2011. 31498, 31499

Min, S. K., Zhang, X., Zwiers, F. W., and Agnew, T.: Human influence on Arctic sea ice detectable from early 1990s onwards. Geophys. Res. Lett., 35, L21701, doi:10.1029/2008GL035725, 2008. 31496

Partain, P.: CloudSat Project, A NASA Earth System Science Pathfinder Mission, CloudSat ECMWF-AUX Auxillary Data, Process Description and Interface Control Document, Version 3.0. Cooperative Institute for Reasearch in the Atmosphere, Colorado State University, 2004.

ACPD
11, 31495–31522, 2011

31501
Ramanathan, V.: Interactions between ice-albedo, lapse-rate and cloud-top feedbacks: An analysis of the nonlinear response of a GCM climate model, J. Atmos. Sci., 34, 1885–1897, 1977. 31498
Ramanathan, V., Cess, R. D., Harrison, E. F., Minnis, P., Barkstrom, B. R., Ahmed, E., and Hartmann, D.: Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment, Science, 243, 57–63, 1989. 31497
Schneider, S. H.: Cloudiness as a global climatic feedback mechanism: The effects on the radiation balance and surface temperature of variations in cloudiness, J. Atmos. Sci., 29, 1413–1422, 1972. 31497, 31498
Schweiger, A. J. and Key, J. R.: Arctic Cloudiness: Comparison of ISCCP-C2 and Nimbus-7 satellite derived cloud products with a surface based on cloud climatology, J. Clim., 5, 1514–1527, 1992. 31499
Sedlar, J., Tjernström, M., Mauritsen, T., Shupe, M. D., Brooks, I. M., Persson, P. O. G., Birch, C. E., Leck, C., Sirevaag, A., and Nicolaus, M.: A transitioning Arctic surface energy budget: the impacts of solar zenith angle, surface albedo and cloud radiative forcing, Clim. Dyn., 37, 1643–1660,, doi:10.1007/s00382-010-0937-5, 2010. 31499, 31510
Serreze, M. C. and Francis, J.: The Arctic amplification debate, Clim. Change, 76, 241–264, 2006. 31496
Serreze, M. C., Holland, M. M., and Stroeve, J.: Perspectives on the Arctic's rapidly shrinking sea-ice cover, Science, 315, 1533–1536, 2007. 31496
Shupe, M. and Intrieri, J.: Cloud radiative forcing of the arctic surface: The influence of cloud properties, surface albedo and solar zenith angle, J. Clim., 17, 616–628, 2004. 31499, 31505, 31507
Simmons, A., Uppala, S., Dee, D., and Kobayashi, S.: ERA-Interim: new ECMWF reanalysis products from 1989 onwards, ECMWF Newslett. 110, 25–35, 2006. 31502
Soden, B. J. and Vecchi, G. A.: The vertical distribution of cloud feedback in coupled ocean-atmosphere models, Geophys. Res. Lett. 38, L12704, doi:10.1029/2011GL047632, 2011.
Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L.: Climate change 2007: The physical science basis. Cambridge University Press, 996 pp., 2007. 31496
Stephens, G. L., Vane, D. G., Boain, R. J., Mace, G. G., Sassen, K., Wang, Z., Illingworth, A. J., O'Connor, E. J., Rossow, W. B., Durden, S. L., Miller, S. D., Austin, R. T., Benedetti,

ACPD
11, 31495–31522, 2011

A., Mirescu C., and the CloudSat Team: The CloudSat mission and the A-Train, Bull. Amer. Meteorol. Soc., 83, 12, 1771–1790, doi:10.1175/BAMS-83-12-1771, 2002. 31499

Stephens, G. L., Vane, D. G., Tanelli, S., Im, E., Durden, S., Rokey, M., Reinke, D., Partain, P., Mace, G. G., Austin, R. T., L'Ecuyer, T. S., Haynes, J., Lebsock, M., Suzuki, K., Waliser, D., Wu, D. Kay, J., Gettelman, A., Wang, Z., and Marchand, V.: CloudSat mission: Performance and early science after the first year of operation, J. Geophys. Res., 113, D00A18, doi:10.1029/2008JD009982, 2008. 31501

Stroeve, J., Holland, M. M., Meier, W., Scambos, T. and Serreze, M.: Arctic sea ice decline: Faster than forecast, Geophys. Res. Lett. 34, L09501, doi:10.1029/2007GL029703, 2007. 31497

Uttal, T., Curry, J.A. , McPhee, M. G., Perovich, D. K., Moritz, R. E., Maslanik, J. A., Guest, P. S., Stern, H. L., Moore, J. A. , Turenne, R., Heiberg, A., Serreze, M. C., Wylie, D. P., Persson, P. O. G. , Paulson, C. A. , Halle, C. , Morrison , J. H. , Wheeler P. A. , Makshtas, A. , Welch H. , Shupe, M. D. , Intrieri J. M., Stamnes K., Lindsey R. W., Pinkel, R., Pegau, W. S., Stanton, T. P., and Grenfeld T. C.: Surface heat budget of the Arctic ocean, Bull. Amer. Meteorol. Soc., 83, 255–275, 2002. 31502

Vavrus, S., Holland, M. M., and Bailey, D. A.: Changes in Arctic clouds during intervals of rapid sea ice loss, Clim. Dyn., 36, 1475–1489, doi:10.1007/s00382-010-0816-0, 2011. 31498

Walsh, J. E. and Chapman, W. L.: Arctic cloud-radiation-temperature associations in observational data and atmospheric reanalysis, J. Clim., 11, 3030–3045, 1998. 31497

Winker, D., Hund, W. H., and Gill, M. C.: Initial performance assessment of CALIOP, Geophys. Res. Lett., 34, L19803, 2007. 31501

Wetherald, R. T. and Manabe, S.: Cloud feedback processes in a general circulation model, J. Atmos. Sci., 45, 1397–1415, 1988. 31498

ACPD
11, 31495–31522, 2011

Arctic clouds and radiation

M. Zygmuntowska et al.

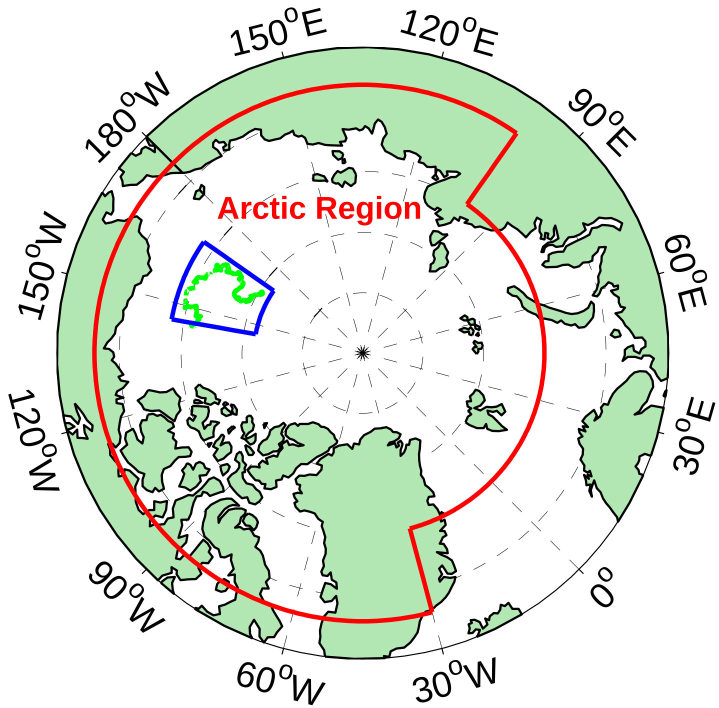

Fig. 1. Arctic Ocean as defined in this study. Ocean grid-points in the area enclosed by the red line are considered for the analysis. The green trajectory shows the drifting ice floe used for the SHEBA campaign and the area enclosed by the blue line is used for comparison with ERA-Interim.

ACPD
11, 31495–31522, 2011

Arctic clouds and radiation

M. Zygmuntowska et al.

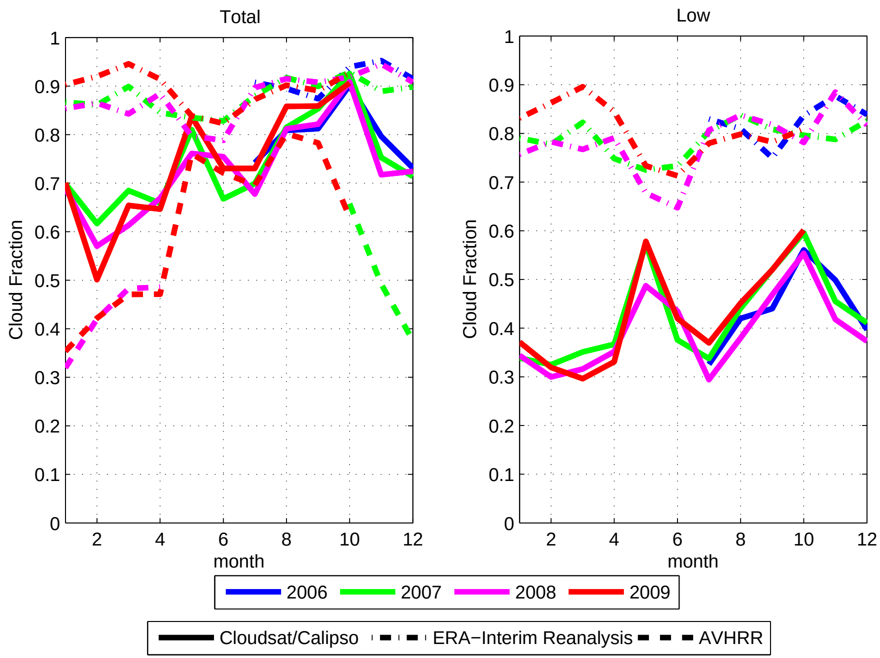

Fig. 2. Annual cycles of total- and low-level cloud fraction from 2006 to 2009 for the Arctic Ocean as derived from CloudSat/CALIPSO, ERA-Interim and an AVHRR-based retrieval from CM-SAF. For low-level clouds no data is available from AVHRR.

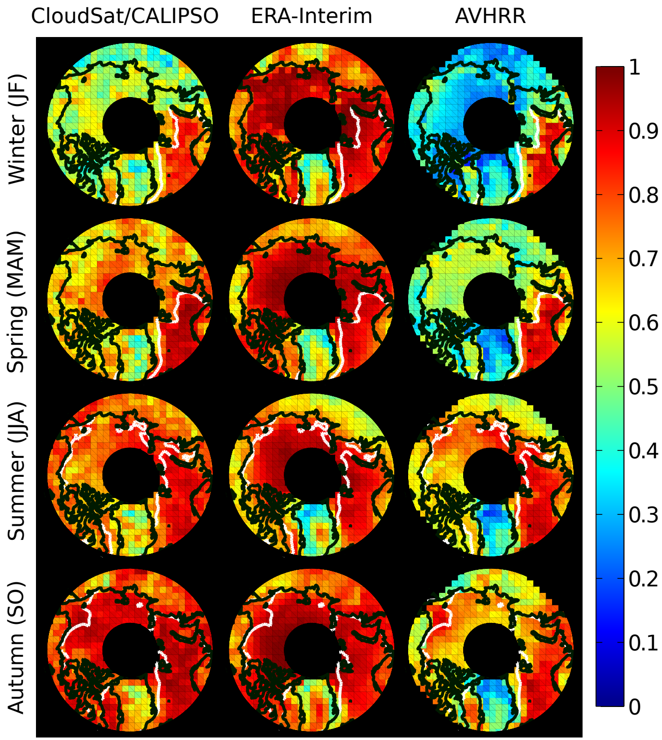

Fig. 3. Geographical distribution of seasonal mean total cloud fraction based on the merged CloudSat/CALIPSO data, for ERA-Interim Reanalysis data and for CM-SAF for 2009. Values for winter are averaged over January and February and autumn only for September and October. The white line indicates the sea ice margin in the four seasons as derived from SSM/I satellite data.

ACPD
11, 31495–31522, 2011

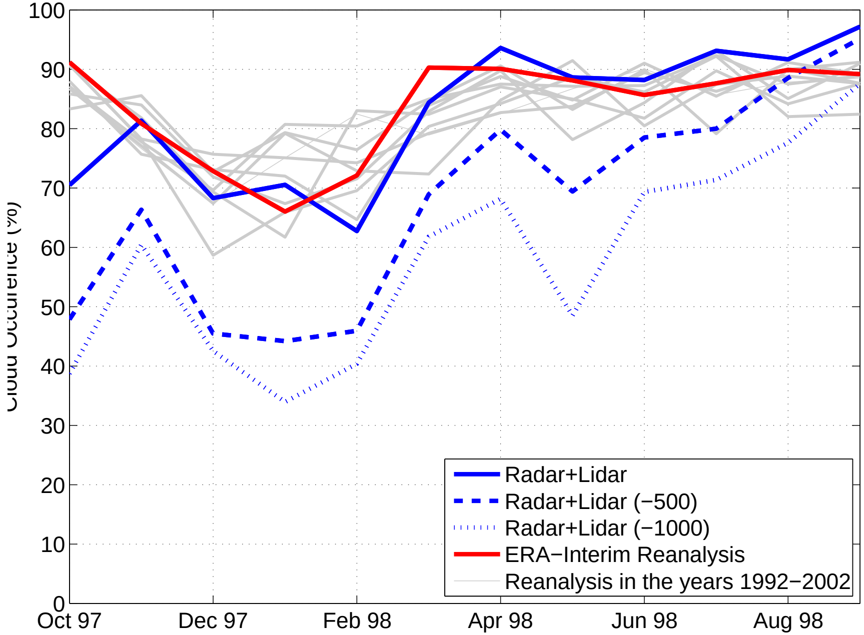

Fig. 4. Total cloud fraction based on combined ground-based lidar and radar observations (blue solid) from the SHEBA field campaign for the period from October 1997 to September 1998, while ERA-Interim total cloud fraction (red solid) is averaged over the blue region shown in Fig. 1, 74–81° N and 145–170° W. Dashed and dotted blue lines show the total cloud fraction obtained while neglecting clouds detected in the lowest 500 m and 1000 m, respectively. Gray thin lines are ten other individual years from ERA-Interim.

ACPD
11, 31495–31522, 2011

Arctic clouds and radiation

M. Zygmuntowska et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◄
►
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

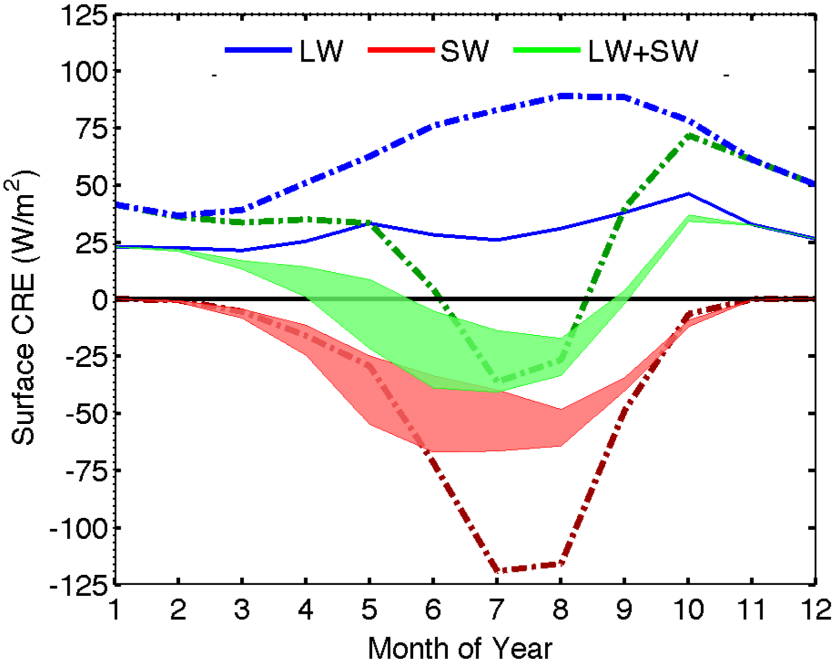

Fig. 5. Annual cycle of the long-, shortwave and net cloud radiative effects over the Arctic Ocean based on 2B-FLXHR derived from CloudSat (solid lines and areas) and on ERA-Interim (dash-dotted lines). The satellite shortwave data has been corrected for the presence of sea ice as described in the text, and the shaded areas depict the sensitivity to these choices. ERA-Interim here uses its native surface albedo, which on average is lower than the assumptions used for CloudSat.

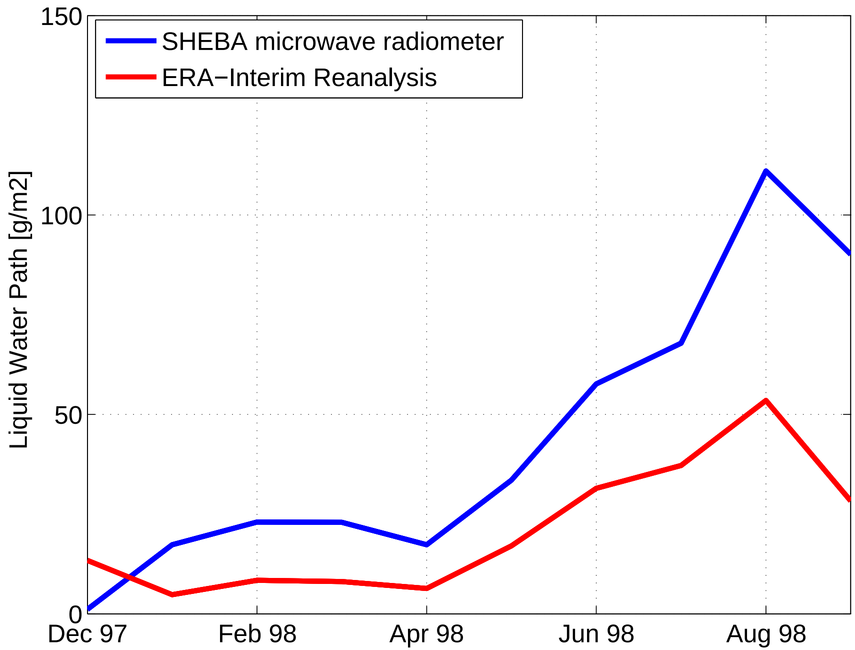

Fig. 6. Comparison of observed and ERA-Interim liquid water path with observations from a dual-channel microwave radiometer during the SHEBA campaign.

ACPD
11, 31495–31522, 2011

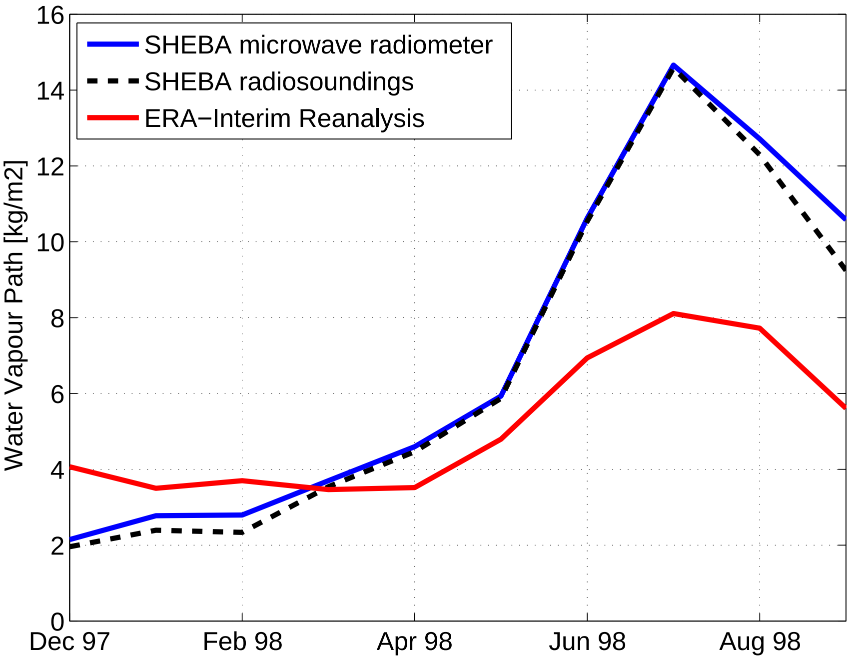

Fig. 7. Comparison of observed and ERA-Interim water vapor path with observations from a dual-channel microwave radiometer and integrated from radiosoundings during the SHEBA campaign.

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ACPD
11, 31495–31522, 2011

Arctic clouds and radiation

M. Zygmuntowska et al.