JP2.4 On Integrating Cloud-Radar-Derived Arctic Ice Cloud Properties into the Radiative Transfer Model "Streamer"

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1. Introduction

Millimeter-wavelength cloud radars can potentially provide a vast dataset on ice cloud properties that can aid research into the radiative behavior of ice clouds. The problem arises, however, of how best to integrate the radar-retrieved ice microphysics within the radiative transfer (RT) simulations. Aside from the radiative effect of the random retrieval errors, two incompatibilities arise:

1. The cloud radar does not sense potentially radiatively-important small particles.

2. The vertically-pointing cloud radar is only weakly responsive to particle habit details that may be consequential to short- and longwave radiation.

In this proceeding we evaluate the impact of these two effects upon the net cloud radiative heating rate using one well-documented case study with available in situ aircraft data on the particle size distributions. On April 28, 1998, an optically-thin single-layer ice cloud advected over the cloud radar during the Surface Heat and Energy Budget of the Arctic experiment (SHEBA;Uttal and co authors, 2002). The cloud optical depth could be independently determined from an Atmospheric Emitted Radiance Interferometer (AERI;Revercomb et al., 1993). A radar estimate of the volume extinction coefficient and particle size is performed (Matrosov et al., 2002), and the radiative transfer code Streamer is utilized for the short- and longwave RT simulations. The conference poster (with more and color plots) is available through http://www.etl.noaa.gov/∼pzuidema.

2. Radar Retrieval of the Volume Extinction Coefficient

A radar-only vertically-resolved retrieval of the particle median size D_o and volume extinction coefficient β has recently been developed (Matrosov et al., 2002). Advantages include: 1) a sole-sensor approach can be applied more often than a multi-sensor method, 2) a direct retrieval of β is more easily compared or tuned against another independent measure of the cloud optical depth τ, 3) a vertically-resolved profile is returned as opposed to a layer-mean value, and 4) once the retrieval of β and D_o are done, and β perhaps tuned, the particle size D_o

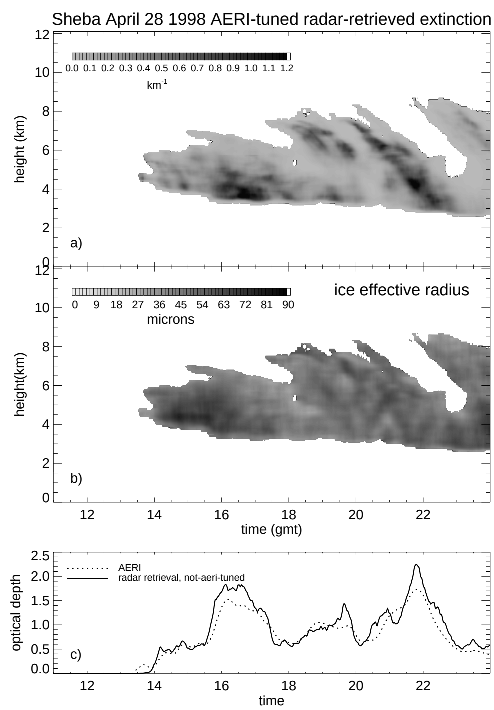

FIG. 1: a) AERI-tuned radar estimate of the volume extinction coefficient, b) effective radius, c) AERI-derived cloud optical depth and original radar-only τ estimate.

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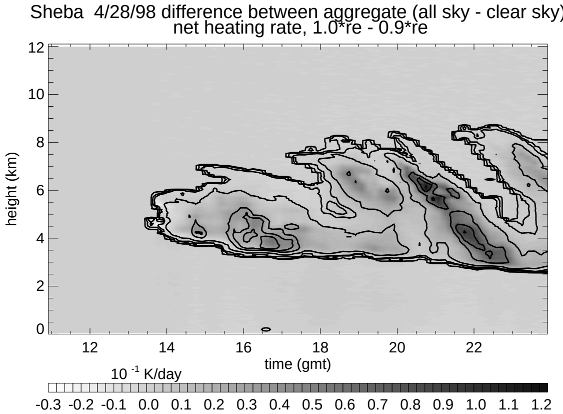

FIG. 2: Difference between the aggregate (all-sky - clear-sky) net radiative heating rate and that calculated for a reduced effective radius 0.9*r_e.

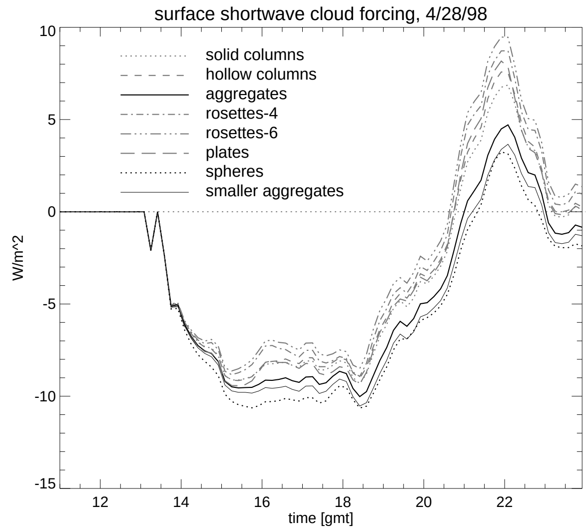

FIG. 3: Surface shortwave cloud forcing for seven different particle habits and for reduced-size aggregates.

can also be independently varied without indirectly altering the value of β.

First, a particle median size D_o is inferred using a Doppler velocity-particle size relationship. Then β is estimated at each vertical level from the radar reflectivity and D_o. For this particular case, the estimation of β can be tuned using the cloud optical depth determined from AERI[1]. Fig. 1a) shows the tuned estimate for β, and panel c) shows cloud optical depth (τ) corresponding to the original radar-only estimate of β as well as the AERI τ estimate. Over the course of 10 hours for this particular case, the radar-only τ is either in agreement with or an overestimate relative to the AERI τ. Throughout the entire SHEBA year, radar-only estimated optical depths were about 25% less than the the AERI-retrieved values in the mean, (S. Matrosov, pers. comm.), consistent with the expectation that the cloud radar can miss small yet radiatively-important particles.

3. The Effective Radius and the Radiative Transfer Simulation

The Streamer code (Key, 2001) was chosen because of its wide use within the Arctic community, its adaptibility for Arctic-condition inputs, its medium-band spectral resolution, and, in particular, its sophisticated treatment of ice clouds. The longwave ice cloud optical properties are derived through parameterizing Mie calculations for ice spheres following the method of Hu and Stamnes (1993). and the shortwave parameterizations are developed for seven different particle habits (Key et al., 2002). 30 different particle size distributions observed by aircraft 2DC optical probes form the basis for the parameterizations.

[1] An infrared absorption optical thickness is retrieved from the 11 μm channel AERI measurement, and an extinction efficiency factor of 2 is assumed to estimate the visible extinction τ. The AERI retrieval of τ is thought to be a more robust and direct measure than can be performed from radar data.

The Streamer code has been modified to accept the high-vertical-resolution cloud radar data. Twice-daily SHEBA soundings of temperature and humidity were used, and the spectral surface albedo measurements of (Perovich et al., 1999) along with the broadband albedo derived from the broadband radiative surface fluxes.

Two issues arise with the use of Streamer. One issue that will perhaps remain specific to the application performed here, is that Arctic clouds were not considered when the ice cloud optical property parameterizations were developed. The second more general issue is that a solid ice density is assumed within the RT model, while the radar retrieval was performed assuming an ice density that decreases with particle size. The radar-retrieved ice particle size cannot be linearly related to the effective radius value expected by Streamer.

An ice particle bulk density-size approximation appropriate for the cloud radar retrieval is

$$\text{bulk ice density} \sim 0.07\text{D}^{-1.1}$$

where D is the individual particle size (Brown and Francis, 1995). This accounts for the observation that as ice particle sizes increase, they tend to take on more complicated shapes that diminish their bulk density, e.g., rosette forms. At the millimeter cloud radar wavelength, the ice particle shape does not become resolved as anything more than a decrease in ice density. A polynomial regression relates the radar-derived D_o to the solid ice-density effective radius expected by Streamer. The solid ice-density effective radius is shown in Fig. 1b.

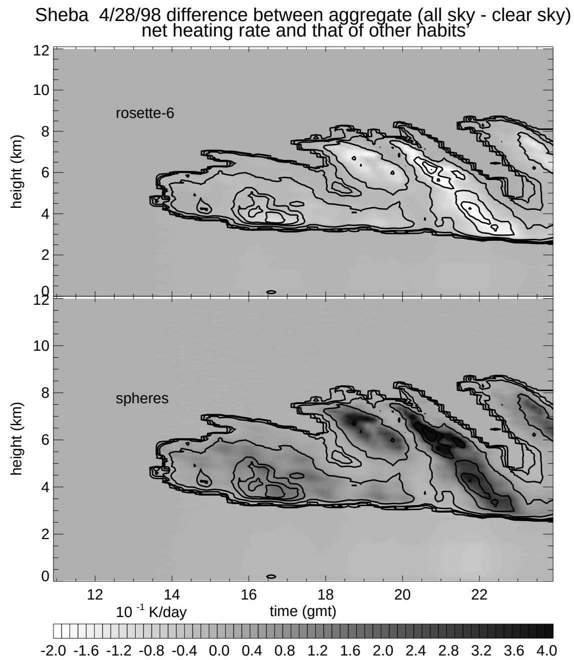

FIG. 4: Difference between the aggregate (all-sky - clear-sky) net radiative heating rate and that of a) rosette-6, and b) spheres. Note units are 0.1*(the shown scale).

4. Results

4.1 *How well is the effective radius estimated by the cloud radar ?*

In situ 2DC optical probe data were collected on this day by the Canadian Atmospheric Service CV-580 instrumented research aircraft during a spiral descent from 23:55 UTC to 00:15 UTC. This data, and the data upon which the Streamer parameterizations are based, are collected in 25 μm bins with the smallest bin centered on 25 μm; particles less than $\sim$ 20 μm are missed. The particle sizes retrieved using the cloud radar and captured by the 2DC probe are thought to be similar for this reason. For this case, in situ and remote estimates of particle size and ice water content agree well (Matrosov et al., 2002).

The SHEBA aircraft particle size distributions showed a high proportion of small particles, and a small proportion of large particles, relative to the Streamer tropical and mid-latitude size distributions. Most particles were irregular aggregates with approximately equal dimensions along both 2DC optical axes.

The Streamer parameterizations are also based on aircraft 2DC optical probe data. To account for the unmeasured small particles, the measured distributions were extrapolated to 12.5 μm (Key et al., 2002; Fu, 1996) using a power law form given by Heymsfield and Platt (1984). We treated the SHEBA aircraft particle size data similarly to estimate a population of particles of size 12.5 μm. The addition of a population of small particles led to a calculated 5-6 % increase in β and a 6 % decrease in the effective radius. Thus, we conclude that the cloud radar overestimated the effective radius by about 5% for this case. Additionally, the ice water content increased 1%, and the radar reflectivity changed negligibly. These changes may be an underestimate, as no particles smaller than 12.5 μm were considered, and the 2DC probe is thought to undercount particles with sizes $\leq$ 100 μm.

4.2 *How does the addition of small particles change the net radiative heating field ?*

Two broadband radiative heating rate calculations were done, with the only difference being that in one calculation, the effective radius was set equal to 90% of the effective radius of the reference case. A spherical particle habit was assumed for $D_o < 36$ μm, and an aggregate shape assumed for the larger particles. Fig. 2 shows the difference in the net radiative heating rate for the two cases. The cloud with the smaller effective radii but the same optical depth showed a slight net cooling relative to the reference cloud, of roughly 5% at most. The physical explanation is that cloud solar absorption is more sensitive to changes in particle size than cloud infrared emission. As particle sizes decrease, solar heating through absorption decreases more rapidly than infrared cooling, and an increase in net cooling occurs. At this high-latitude site in April, the Sun is above the horizon about 20 hours out of the day.

4.3 *What is the impact of particle habit on the net radiative heating rate?*

Figure 3 shows the surface shortwave cloud forcing for seven particle habits and for aggregates at 90% the original effective radius (all particle smaller than 36 μm are still considered spheres). Solar noon occurs roughly at 22 UTC. An error in identifying the correct habit shape can generate an error of up to 6 W m^{-2} in the surface shortwave cloud forcing for this case.

Figure 4 shows the difference in the net radiative heating rate between a cloud composed of aggregates, and a) of bullet rosettes with 6 branches, and b) of spheres. These habits showed the largest differences from aggregates in their net radiative heating rate field. The cooling is mainly a function of the particle volume. Spheres, with their high volume to area ratio, cool the most efficiently for a given effective radius, while rosettes with their low volume to area ratio cool the least efficiently. For this case, a cloud with an inaccurately-determined particle shape can produce a difference in the local radiative heating of up to 15% of either positive or negative sign.

5. Conclusions and Summary

An evaluation was done of realistic errors that can be produced in Arctic radiative heating rate fields if, when

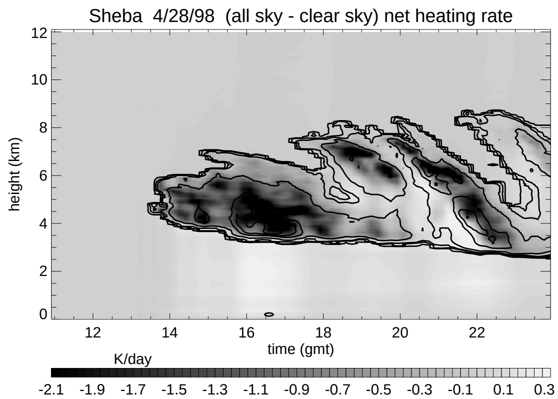

FIG. 5: Best estimate of the (all-sky - clear-sky) net radiative heating rate for this case

using cloud radar-derived microphysical properties as inputs, 1) particles too small to be detected by the radar are included, and 2) particle habit is inaccurately specified. In situ aircraft data were used to estimate the number of missed small particles and to establish a reference particle habit. We find:

1. The neglect of small particles can cause underestimates of up to 5% in the local net radiative heating rate.

2. The inaccurate specification of ice particle habit can generate differences of up to 15% in local net radiative heating rates from the reference case. These differences can be of either sign.

Based on one case study alone:

1. The initial neglect of small particles by cloud radar can be easily accounted for with a correction to the effective radius input into Streamer

2. Significant error in the cloud radiative heating rate calculation can result from a lack of a priori knowledge of the ice particle habit

The best estimate of the net radiative heating rate is shown in Fig. 5. It uses the volume extinction coefficient shown in Fig. 1a, effective radii values that are 95% of what is shown in Fig. 1b (consistent with the results of Section 4.1), and assumes an aggregate shape for $D_o >$ 36 μm, and spheres for smaller particle sizes.

Further work will build towards developing a long-term dataset on Arctic cloud radiative heating rates. More aircraft data will be examined, including FSSP data to estimate the small particle size population. The extinction efficiency factor of 2, used within the AERI optical depth estimate, may be modified.

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