Observations and simulations of Three-Dimensional Radiative Interactions between Arctic Boundary layer Clouds and Ice Floes

M. Schäfer1, E. Bierwirth1,2, A. Ehrlich1, E. Jökel1, M. Wendisch1

1Leipzig Institute for Meteorology, University of Leipzig, Leipzig, Germany
2Now at: PIER-ELECTRONIC GmbH, Nassauerstr.33-35, 65719 Hofheim-Wallau, Germany

1. Introduction
- Highly affects surface albedo in the Arctic
- Affects cloud radiative forcing
- Large variations on small horizontal scales
- Airborne, imaging spectrometer measurements
- High spatial and spectral resolution
- Investigation of cloud radiative effects above heterogeneous surface

Fig. 1: Cloud radiative forcing at the surface as a function of the surface albedo. Simulations performed for a cloud with optical thickness of \( \tau = 10 \) and for two different solar zenith angles. (1)

Clouds above ice and open water

Fig. 2: VERDI flight track and true-color MODIS image (Aqua: 250 m resolution) of 17 May 2013. (2)

For visible wavelength range:
- Over dark ocean surface, \( \tau \) can be retrieved
- Over bright sea ice surface, \( \tau \) cannot be retrieved
- Ice mask necessary

Fig. 3: Imaging spectrometer AisaEAGLE

Fig. 4: Scheme of the airborne measurement principle using the imaging spectrometer AisaEAGLE. Adapted from (4).

2. VERDI Campaign Study of the Vertical Distribution of Ice in Arctic Clouds
- Invuk Airport, Canadian Arctic
- 25 April – 17 May 2012: 13 Flights
- Platform: AWI’s Polar-5 research aircraft (Bawler B167)
- Instrument: AisaEAGLE [3]
- 488 spectral pixels

Ice Floe Size

Fig. 6: Averaged radiances (color coded) at 645 nm wavelength measured perpendicular to the ice edges shown in Fig. 5. All radiances values used for the average of the ice edge cases are given as gray lines. (2)

- Ice mask
- Threshold derived from minimum values of frequency distributions

- In case of clouds:
  - Bright bands next to ice edges
  - Radiance enhanced above dark ocean
  - Radiance reduced above bright sea ice

- Related to 3D radiative effects:
  - Influence on cloud retrieval results

3. Observations

Fig. 7: Normalized distributions of the frequency of occurrence of the radiances measured during the three cases presented in Fig. 5. Additionally, the frequency distributions over sea ice and dark ocean water are shown.

4. Simulations

Cloud Optical Thickness:

Fig. 8: Simulated mean radiance across an ice edge for clear sky and cloudy (\( \tau / \tau_0 = 10/2 \)) between 0 and 300 m (\( \tau_0 = 13 \) cm) conditions. The white area illustrates bright sea ice, the gray area dark ocean water. Included are results of 3D and 2D simulations, as well as the average of the reflected radiance measured perpendicular to the ice edge in Fig. 5. (2)

Cloud Altitude and Geometrical Thickness:

Fig. 9: Simulated radiance for clouds at different altitudes (500 m, cloud geometrical thickness) and with different geometrical thickness (cloud base at 0 m) in the vicinity of an ice edge. (2)

Ice Floe Size

Fig. 10: Simulations of the critical distance \( d_c \) as a function of ice floe size and different values of cloud optical thickness. Asymptotic maximum values of \( d_c \) marked with dotted blue lines. The cloud is at altitudes between 500 and 1000 m. (2)

5. Retrieval of \( \tau \) and \( \text{eff} \)

- Model cloud: \( \tau = 10, \text{eff} = 15 \mu \text{m}, h_c = 500-1000 \text{ m}, \) over circular ice floe with \( r = 6 \text{ km} \)
- 3D simulation of upward radiances

Fig. 11: Retrieval grid using nadir radiance at 645 nm and the ratio of the nadir radiance at 0.5λ/λ = 1.35 nm/375 nm. The black cross marks the exact cloud properties. (2)

6. Conclusions and Outlook

- In the vicinity of ice edges:
  - Enhanced radiance above dark ocean water
  - Reduced radiance above bright sea ice

- Mainly controlled by: \( \tau \), cloud altitude and geometrical thickness, ice floe size
- Overestimation of \( \tau \) and \( \text{eff} \) up to 90 \% and 30 \%, respectively

- Cloud structure from retrieved fields of \( \tau \)
  - Size of cloud structures from autocorrelation functions across/ along flight track

Fig. 12: Overestimation of the cloud optical thickness of effective radii as a function of the distance to the edge of the ice floe. The model cloud at an altitude of 300 m to 1000 m had \( \tau = 10 \) and \( \text{eff} = 13 \mu \text{m}. \) (2)

Fig. 13: Retrieved field of cloud optical thickness. Arrows mark direction of averaging for data shown in Fig. 14.

Fig. 14: Single (dotted lines) and averaged (solid lines) autocorrelation functions for positions marked in Fig. 12.