Impacts of Aerosol Concentration Variability on Turbulence in Convective Low Level Mixed-phase Clouds in the Arctic

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Motivation

Arctic low-level mixed-phase clouds are unfortunately not properly represented in weather forecast and climate models. How can we gain a deeper understanding of processes there and their impact?

see Abstract

more Background

Research Question

How does the change in CCN concentrations affect thermodynamic and turbulent properties of boundary layer?

Observations

about observations

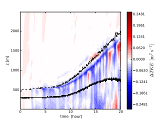
Methodology

High-resolution large eddy simulations with an enhanced bulk scheme for mixed-phase microphysics to model the impact of cloud processes on a developing cloudy boundary layer.

General methodology

Microphysics

Results



General Results

Impact of TKE

Conclusions

Lower CCN concentrations generally lead to higher ice production, resulting into changes in turbulence budget.

more Conclusions

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Abstract:
Arctic mixed-phase clouds are still not properly represented in weather forecast and climate models. Recent field campaigns in the Arctic have successfully probed low level mixed-phase clouds, however it remains difficult to gain understanding of this complex system from observational datasets alone. Complementary high-resolution simulations, properly constrained by relevant measurements, can serve as a virtual laboratory that provides a deeper insight into a developing boundary layer in the Arctic.
Our study focus on the impact of variability in cloud condensation nuclei (CCN) concentrations on the turbulence in Arctic mixed-phase clouds. Large-Eddy Simulations of convective mixed-phase clouds over open water were performed as observed during the ACLOUD campaign, which took place in Fram Strait west of Svalbard in May and June 2017. The Dutch Atmospheric Large Eddy Simulation (DALES) is used including a well-established double-moment mixed-phase microphysics scheme of Seifert Beheng.
The results highlight various impact mechanisms of CCN on the boundary layer thermodynamic state, turbulence, and clouds. Lower CCN concentrations generally lead to decreased turbulence near the cloud top. However, they can also enhance the turbulence in the lower part of the boundary layer due to increased amount of sublimation of ice hydrometeors. Further implications for the role of mixed-phase clouds in the Arctic Amplification will be discussed.

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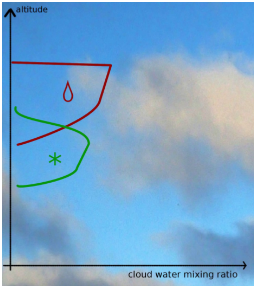
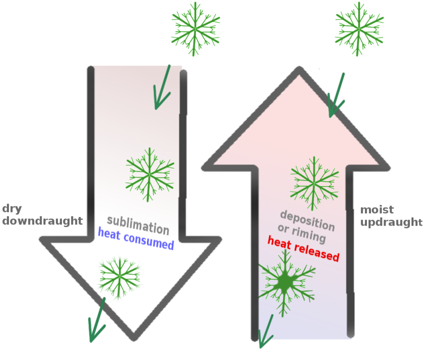
Background



In low-level mixed-phase clouds in the Arctic, liquid phase and ice phase often co-exist. There are number of interactions between ice and liquid hydrometeors. The saturated vapour pressures above ice and liquid differ.



Rapid growth of ice particles by deposition in saturated areas, as well as sublimation of ice particles in sub-saturated areas affects heat budget, resulting in changes in buoyancy.

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forward to Observations

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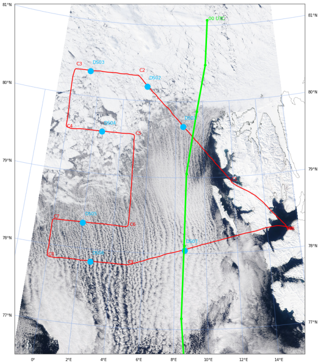
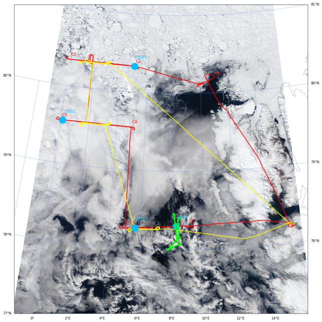
Model Cases

We selected two observed cases of developing mixed-phased clouds over open water.



RF05 — on 25 May 2017
Illustrative example of a CAO with a gradual with a developing cloud streets.



RF20 — on 18 June 2017
Boundary layer is characterised by warmer temperatures and a thicker layer of low-level clouds.

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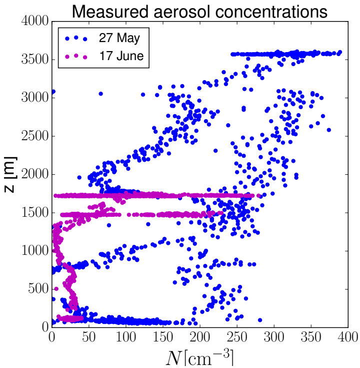
further to aerosols

Observations – Aerosol concentrations



Observations from P6 aircraft indicated high variability in concentrations of aerosols in the Arctic troposphere.

more about observations

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Observations - ACLOUD campaign

(reproduced from www.ac3-tr.de/)

The *Arctic CLoud Observations Using airborne measurements during polar Day* (ACLOUD) campaign took place from 23 May to 26 June 2017 in Arctic, mostly in the vicinity of Svalbard. Together with its sister campaign, Physical feedbacks of Arctic planetary boundary level Sea ice, Cloud and AerosoL (PASCAL), they were organised as part of the ongoing $(\mathcal{AC})^3$ research program.

The ACLOUD campaign provided valuable observations of spring-time lower troposphere. It was characterised by collocated airborne observations performed by aircraft P5 and P6. P5 mostly conducted measurements with radiative instruments, while P6 provided in-situ observation with an assortment of aerosol and cloud particle probes.

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Model Framework

Fine-scale semi-idealised model cases are based on observed weather situation during ACLOUD

- model software: Dutch Atmospheric Large-Eddy Simulation (DALES)
- microphysics scheme for resolving mixed-phase clouds more on microphysics scheme
- demi-lagrangian frame following the trajectory of an air parcel more on LES setup
- initial conditions and large-scale forcing
  - combination of analyses and short-range forecasts [van Laar et al., 2019]
  - warm bias in initial conditions corrected based on dropsonde profiles upstreams following [Neggers et al., 2019]
  - in a near future also from regional model (Schemann, V.et al.: *Exploring model hierarchies for large-eddy simulations of observed Arctic cold air outbreaks*)

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straight to results

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Cloud Microphysics Scheme

Seifert & Beheng (S&B) parameterization scheme is a full **2-moment bulk** parameterization scheme for **mixed-phase microphysics**
[Seifert & Beheng, 2006].
This scheme was previously tested both for simple single-layer clouds and for multilayer clouds.

Main features:

- all three phases of water: ice, liquid water, water vapour
- five hydrometeor species: cloud drople, raindrop, cloud ice, snow, graupel
- approximating collisions efficiencies of hydrometeors
- separate paramaters for concentration of CCN and ICN
- ice nucleation rates affected by turbulent terms

The S&B has been included in a number of atmospheric models (ICON, UCLES, etc.).

Our enhanced implementation of S&B scheme in (**DALES**):

- CCN concentration treated as prognostic variable
- removal of CCN by precipitation taken into account
- cloud droplet number concentration is part of initial conditions
- latent heat of freezing included in the heat budget

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LES setting

- fine-scale resolution
  - horizontal resolution 50 m
  - vertical resolution decreasing with altitude

    5 m by the surface, 50 m at 3000 m
- 6x6x4 km^3 and 12x12x4 km^3 domains
- full radiation scheme

Sets of simulations

Based on the variability in observed CCN concentrations in the region, we set a model ensemble with initial CCN number concentrations:
20, 40, 60, 100, 200, 250 cm^{-3}

Concentration of ice nucleating particles is for simplicity kept constant.

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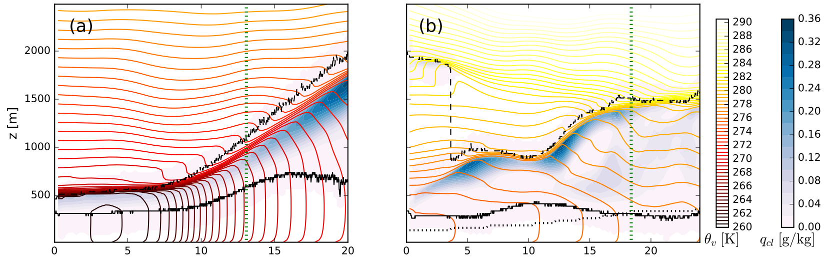
Results – Thermodynamic state & evolution

We selected two observed cases of developing mixed-phased clouds over open water.



RF05 — on 25 May 2017
Illustrative example of a CAO with a gradual deepening of the Arctic mixed layer.

RF20 — on 18 June 2017
Boundary layer is dominated by a thicker layer of low-level clouds that are continue deepening due to cloud-top cooling.

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continue to more results

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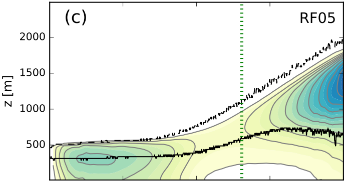
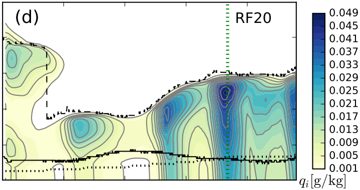
Results – ice water content





Ice mostly in the lower part of clouds.

Ice produced mostly in the upper and middle part of clouds.

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further to TKE

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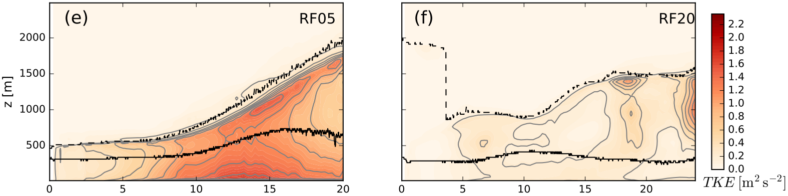
Results – turbulent kinetic energy



Higher TKE due to strong surface forcing.

TKE generated mostly by the circulation within the cloud layer.

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further to impact of CCN

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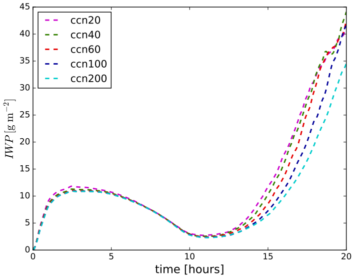

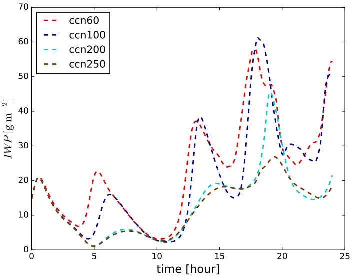

In the cold temperatures and strong surface forcing, there are relatively small differences in ice water path between model runs with different CCN concentrations.

In slightly thicker and warmer clouds with the circulation driven by cloud top forcing, there are significant differences between model runs.

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forward to impact on TKE

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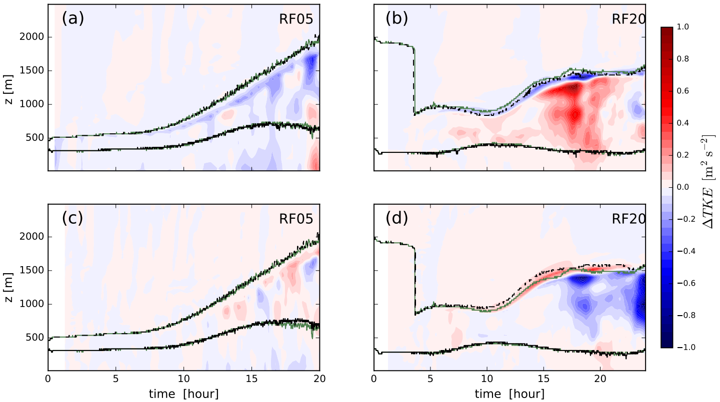
Impact of CCN concentrations on TKE



a) and b) show the difference between ccn 60 and control in RF05 and RF20,
c) and d) show differences between ccn 200 and control in RF05 and RF20
In RF20, lower CCN concentration results in more turbulence in the mid part of boundary layer.

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Conclusions

- Ice hydrometeors affect the the turbulent kinetic energy budget
- in the clouds driven by cloud top cooling, lower CCN concentration result in:
  - more ice production
  - removal of water by ice precipitations
  - decreased cloud-top turbulence
  - increased turbulence in the lower portions of cloud layer

Further Plans

- Publication on the impact of CCN concentration on thermodynamic properties of boundary layer: *The Impact of CCN Concentrations on the Thermodynamic and Turbulent State of Arctic Mixed-Phase Clouds over Open Water* (publication in review)
- estimation of radiative budget
- new case studies based on observations during MOSAIC campaign

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