Cloud Macro- and Microphysical Properties as Coupled to Sea Ice Leads During the MOSAiC Expedition

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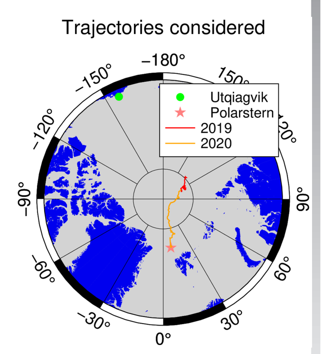
1.- Research Objectives

The study focuses on the observation of Arctic mixes-phase clouds and sea ice leads to address the following research questions:



- Are cloud properties influenced by the presence of sea ice leads?
- Does coupling/decoupling of clouds to moisture-layers impact the cloud's properties?

We focus is wintertime/early spring legs 1 to 3 of the *MOSAiC* expedition [1]. Instrumentation and data set are provided by the Atmospheric Radiation Measurement's (ARM) Mobile Facility 1 (AMF-1) and by the OCEANET-Atmosphere container from TROPOS.

2.- Coupling of Sea Ice and Clouds

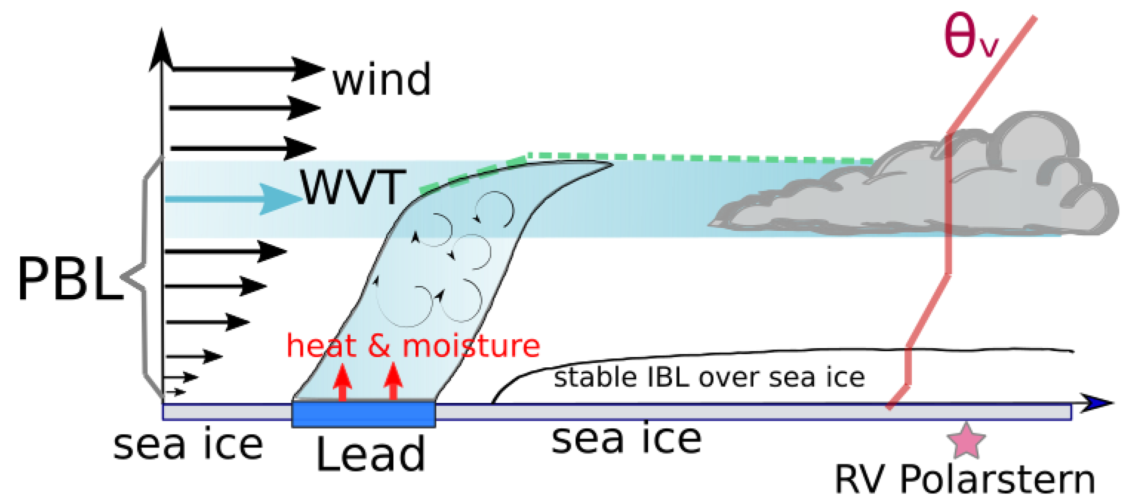


Figure 1: Sea ice interaction with observed clouds. Adapted from [7]

Daily sea ice lead fraction (LF) is obtained based on the divergence calculations from consecutive Sentinel-1 SAR scenes [4]. Sea ice concentration (SIC) is provided by the University of Bremen [5]. Fig. 2 summarizes the LF and SIC during *MOSAiC* wintertime.

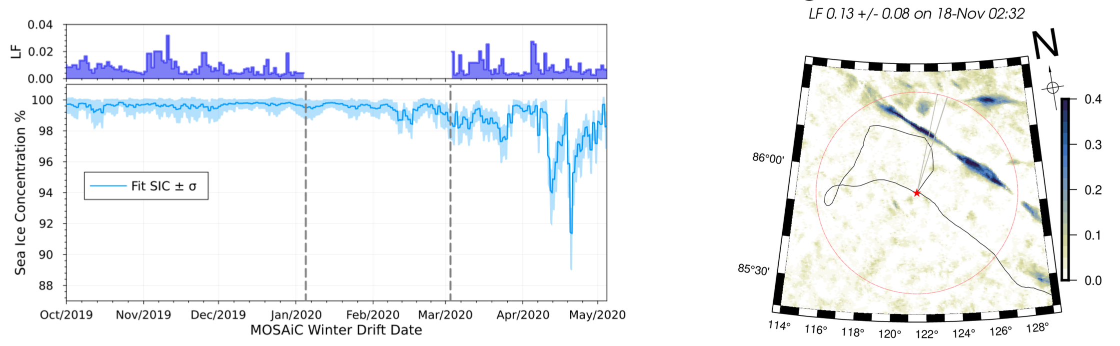


Figure 2: Left: LF and SIC, vertical dashed-grey lines mark the Sentinel-1 data gap. Right: case study 18 Nov 2019.

We relate sea ice lead fraction to cloud observations above RV *Polarstern* following:

- LF products is analyzed within 50 km around the RV *Polarstern* (red star in Fig. 2, right) with updated coordinates every minute.

- Sea ice - atmosphere coupling conceptual model

Vertical gradient of water vapour transport (∇WVT) is calculated from specific humidity q_v [g g^{-1}] and horizontal wind $\vec{v}_w$ [m s^{-1}] from radiosonde profiles, following

$$\nabla \mathrm{WVT} = -\frac{10^2}{g} \left| q_v \cdot \vec{v}_w \right| \frac{dP}{dz} \qquad (1)$$

The direction of maximum transport (see grey lines in Fig. 2) is used to relate LF with zenith observations at RV *Polarstern*.

- Planetary boundary layer height (PBLH)

Estimated via the bulk Richardson number 2, PBLH is used as top layer below which the maximum ∇WVT is localized:

$$Ri_b(z) = \frac{g}{\theta_v} \frac{\Delta\theta_v \, \Delta z}{(\Delta u)^2 + (\Delta v)^2} \qquad (2)$$

3.- Cloud-sea ice coupled case study 18th Nov 2019

Cloudnet target classification is used to determine cloud macro- and microphysical properties. Radiosondes are used to obtain information on the thermodynamic states of the atmosphere, e.g. θ_v, ∇WVT, wind vectors, and Ri_b.

- Synergy of the ship-based zenith observations are needed to apply the Cloudnet classification algorithm.

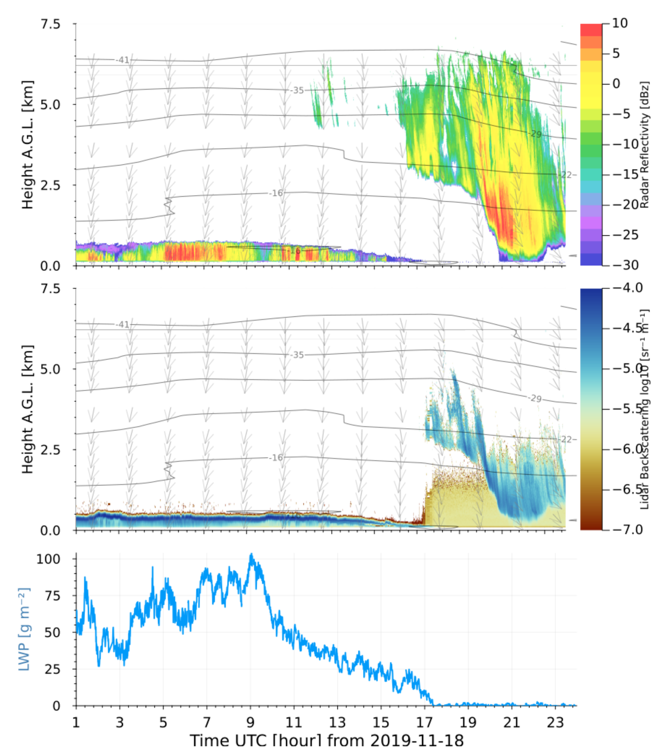


Figure 3: From top to bottom: ARM KAZR cloud radar reflectivity, ARM ceilometer backscattering coefficient, liquid water path from HATPRO microwave radiometer [2].

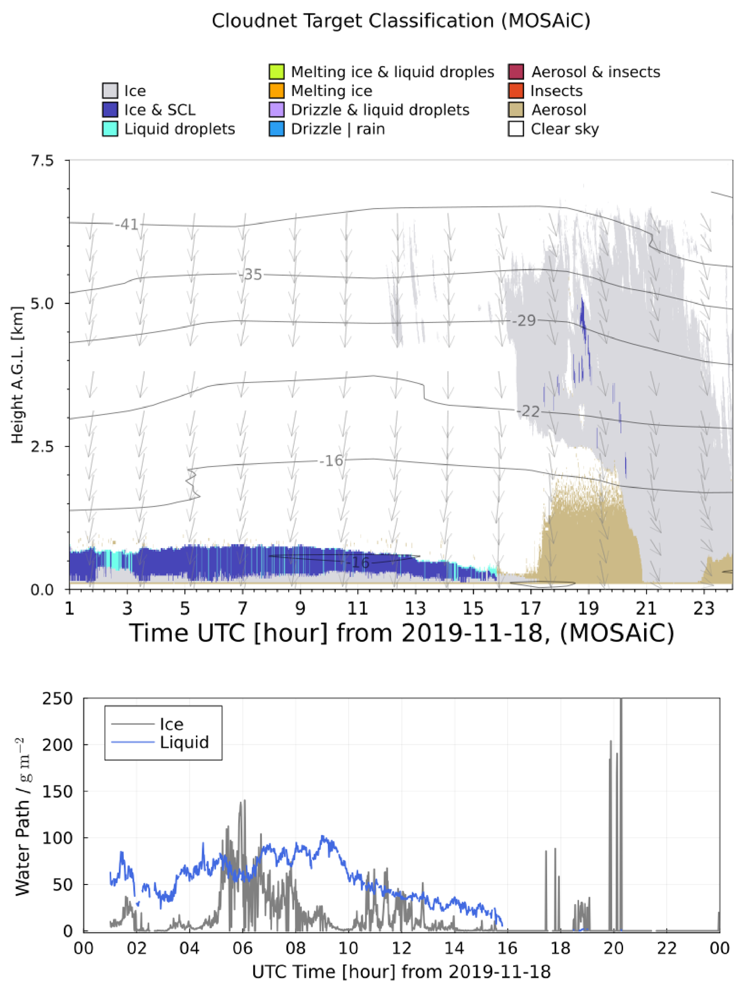


Figure 4: Top: Cloudnet classification from the measurements in Fig. 3. Bottom: LWP and IWP for the lowest layer detected. Note that only of mixed-phase clouds are considered.

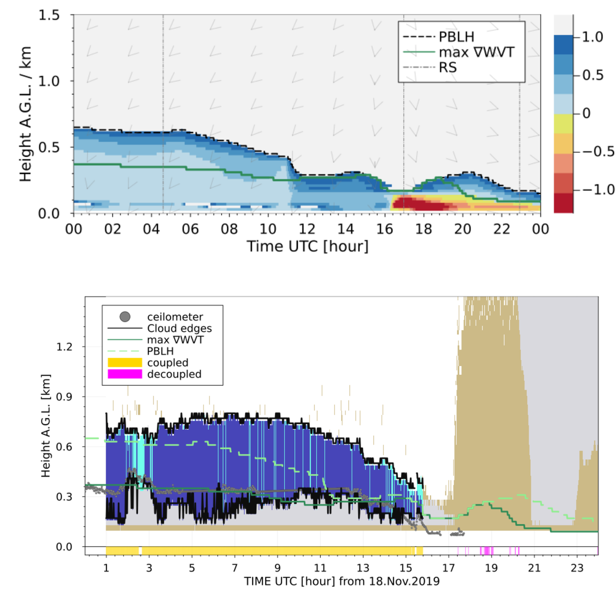


Figure 5: Top: Ri_b for lowest 1.5 km, PBLH critical Ri_b=1. RS denotes times of radiosonde launches. Bottom: Close-up of Fig. 4 with PBLH (dashed-light-green), max ∇WVT (green), and cloud bottom and top heights (black lines), and cloud base by the ceilometer (dotted-grey). Coupled status is shown along the x-axis.

The wind direction at max ∇WVT provides the relevant information to link sea ice LF to the cloud observation above RV *Polarstern*. LF is considered from a region determined by the wind direction with center at RV *Polarstern* to 50 km radius (grey lines in Fig. 2, right).

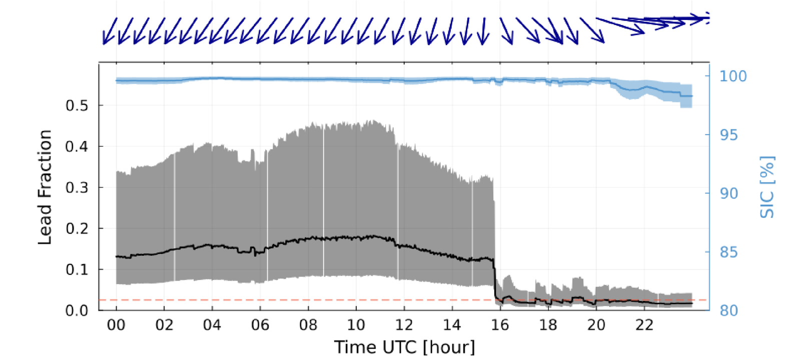


Figure 6: LF extracted from Fig. 2 (right) based on 1-minute wind direction at the max ∇WVT. For reference the wind vectors at max ∇WVT (top panel) and SIC for the same region is also shown in light-blue (right y-axis).

From Fig. 6 the 1-minute LF statistics can be related to the corresponding micro- and macrophysical properties of clouds derived from Cloudnet. In order to reduce variability the following results are averaged in 15 minutes intervals i.e. every point represents ≈ 15 observations and bars are their variance.

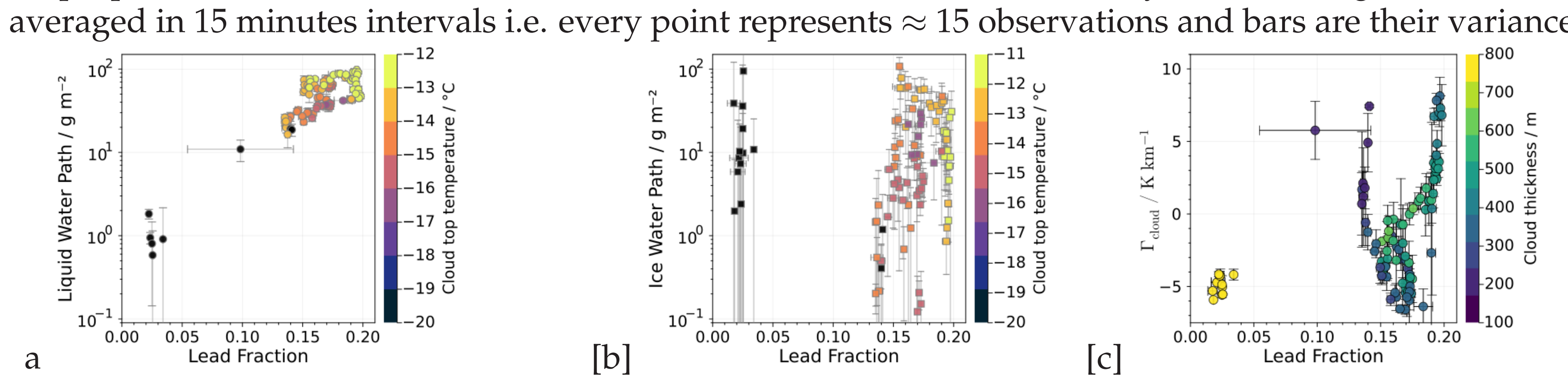


Figure 7: [a] mean single cloud layer LWP vs. LF (black-line in Fig. 6) with colour-coded cloud top temperature. [b] Same but for IWP of same cloud layer. [c] Γ_{cloud} as defined in Eq. 3 vs. LF with colour-coded cloud thickness.

$$\Gamma_{\mathrm{cloud}} = \frac{\Delta T}{\Delta H} = \frac{T_{top} - T_{base}}{CTH - CBH} \qquad (3)$$

Fig. 7 [c] shows the gradient of cloud temperature defined as Eq. 3. The most negative Γ_{cloud} are close to a moist adiabatic lapse-rate. Positive values indicate a temperature inversion at cloud top.

4.- Statistical Results

Based on the analysis in Box 2 & 3 and applied to the whole wintertime data from Nov 2019 to April 2020, the following results are found:

- Cloud coupling classification: criteria based on the virtual potential temperature θ_v and location of maximum ∇WVT below PBLH. The θ_v is analyzed to classify cases where the WVT is coupled or decoupled to the cloud mixing layer.

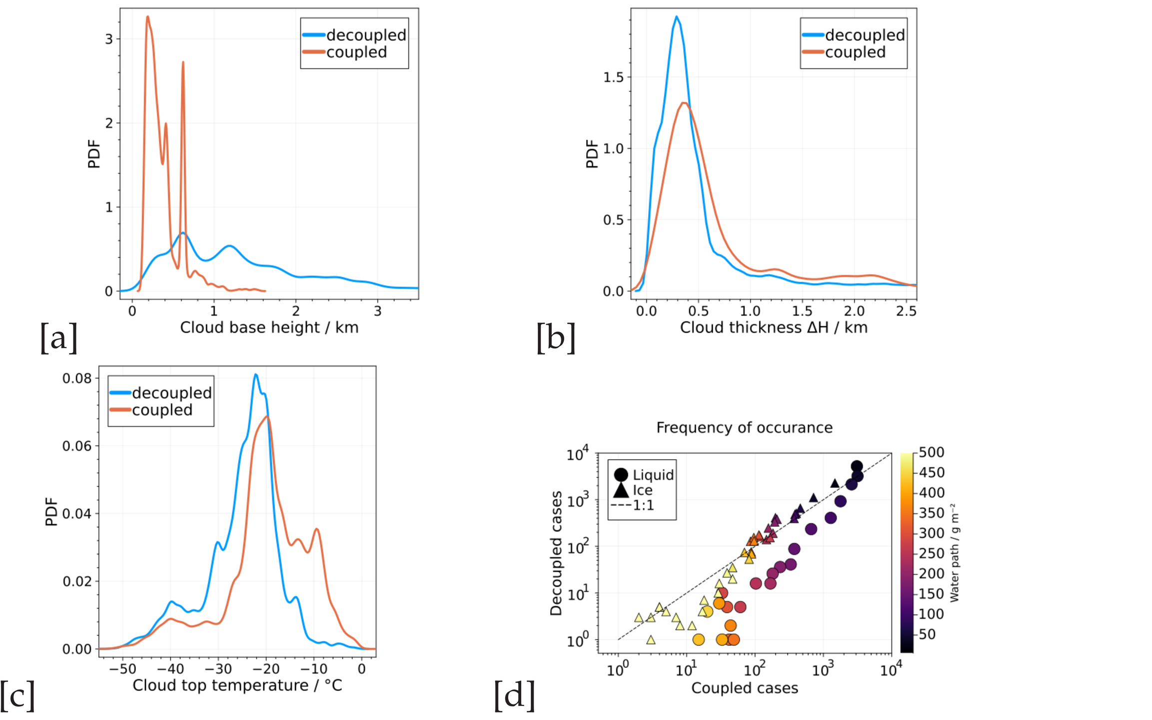


Figure 8: PDF for cloud-base height [a], -layer thickness [b], -top temperature [c], and [d] number of occurrences of coupled (red) and decoupled (blue) observations.

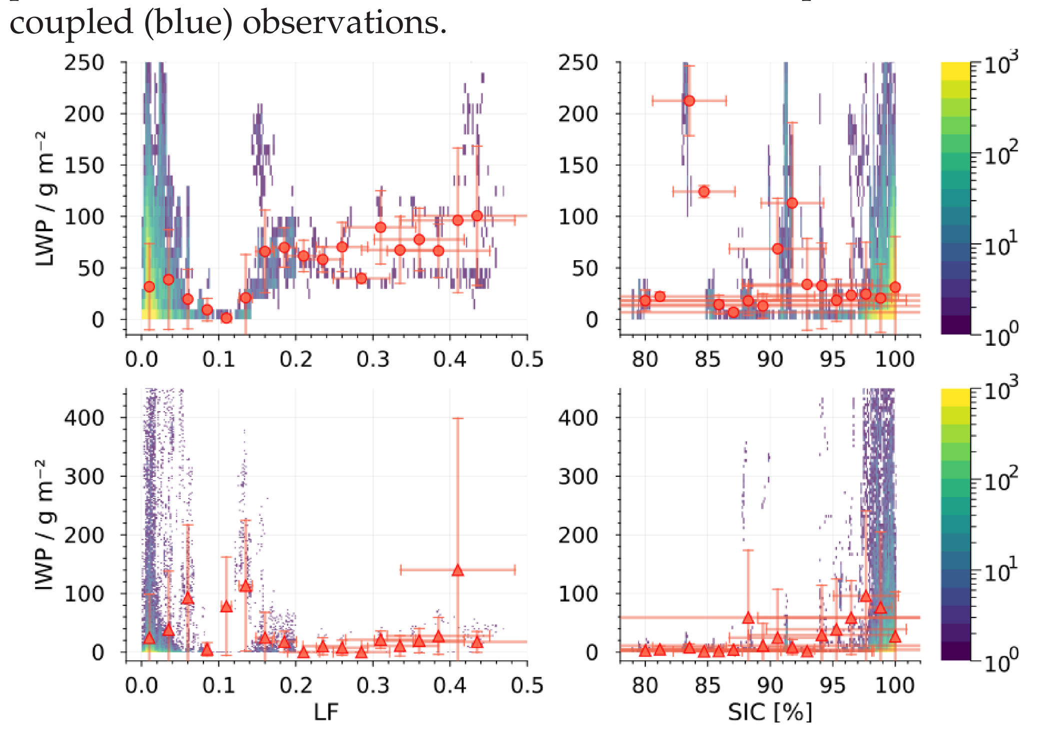


Figure 9: Statistics for LWP vs LF (top left) and LWP vs SIC (top right), and IWP vs LF (bottom left) and IWP vs SIC (bottom right)

5.- Conclusions

- Relating cloud observations with LF upwind with water vapour transport as conveying mechanism for the coupling as a plausible approach,
- When Leads are present, coupled clouds with larger LWP are more frequent,
- Increasing of LWP with LF (decreasing of SIC),
- Ice water shows no clear relation with sea ice LF or SIC,
- Cloud top temperature is warmer and cloud layer thicker for coupled obs.,
- Confirmation that coupled clouds are mainly low level clouds (similar for Utiqiaġvik, Alaska [6]),

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