

# Answers for Reviewer 2

First, we would like to thank the second reviewer for its time and for its positive and constructive review. Below we respond to the specific comments. As requested by the reviewer, we also show some additional results and revised the text in the manuscript.

## 1 Overview

This study is based on the analysis of satellite observations of clouds and sea ice concentration in order to explain the cloud onset occurring from March to May in the Arctic.

The authors used the CALIOP-GOCCP lidar observations from 2008 to 2020 to determine cloud layer phases (liquid, ice and unclassified) and their occurrences. Sea ice concentration is determined from NSIDC observations, and temperature and humidity data are obtained from ERA5 reanalyses. In addition, analyses of ground based data (lidar observations and radiosoundings from the MOSAIC campaign) are included.

The results highlight that, in addition to the supply of moisture contributing to the increase of cloud occurrence during Arctic spring, the rise in air temperature (due to more solar radiation from March to May) plays a major role in the increase of the occurrence of liquid containing cloud. The authors conclude that the increase of temperature alters the balance of cloud phase formation, favoring the liquid phase formation at the expense of ice phase.

## 2 General comments

The paper is well written and well structured. The observations, as well as the methodology, are well described. In particular, the authors take care to apply the same method for both space and ground based observations. They demonstrate that water vapor transport is not a limiting factor for the spring cloud onset. They suggest that ice production processes lead to a depletion of moisture in early spring. They assume that, later during spring, the increase in air temperature is responsible for the transition from ice dominant clouds to liquid dominant clouds.

In my opinion, the goal of this study is clear and of interest to the scientific and Arctic communities. The data and methodology used are very well appropriate. Nevertheless, the main conclusion highlighting that liquid cloud amount increase with temperature on a global average is rather well established, and not particularly very new.

We would like to emphasize that the main contribution of this study, in our opinion, goes beyond documenting a temperature–phase relationship. Specifically, we first highlight that the increase in cloudiness over sea-ice between the first week of April and the first week of May is spatially homogeneous over the sea-ice and mainly due to an increase of liquid-containing optically thick clouds. The remainder of the paper disentangles the relative roles of moisture and energy transport from the mid-latitudes and solar radiation in driving this spring cloud onset over the Arctic sea-ice. (1) We assess the moisture transport contribution and show that, already in March, the moisture transported over the sea-ice is sufficient to support a "close to saturation" state. Indeed, it represents a larger fraction of the atmospheric moisture stored over sea-ice than later in May. This indicates that a lack of water vapor is unlikely to be the limiting factor for the timing of the spring cloud onset. (2) In parallel, we show that the springtime temperature rise over sea ice, mainly driven by the rapid seasonal increase in incoming solar radiation with no contribution by meridional energy transport, shifts the phase balance toward more liquid-containing clouds, thereby enabling the observed transition to optically thicker, liquid-containing, low-level clouds. Taken together, our results support the interpretation that the seasonal cycle is primarily forced by the increase of solar radiation, while strong moisture transport and other advection processes mainly modulate cloudiness on synoptic and daily

timescales. Therefore, we believe this study helps clarify the relative importance of the mechanisms driving the spring increase in cloudiness over Arctic sea ice and provides a context for future studies on the daily variability of cloudiness over the Arctic sea-ice. We thank the reviewer for this general comment, which motivated us to clarify the scope and reframe the manuscript around the relative roles of moisture/energy transport and solar radiation driven spring warming in setting the spring cloud onset.

The study could be made more robust and substantially improved by accounting for the interannual variability of cloud occurrences and by investigating deeper the link between cloud onset and additional environmental parameters (for example: warm air intrusions, dynamics and stability conditions, surface coupling. . . ). Below are some ways to enhance the study before publication.

- First, the results are based on averages over the entire Arctic sea ice region and a long period of 13 years. The authors should study more in detail the interannual variability of cloudiness, sea ice concentration and thermodynamical parameters (temperatures, humidity). The extensive database (13 years, almost the entire Arctic region) makes such an analysis possible. For example: is there a link between the interannual variability of sea ice coverage and cloud occurrences (and phase), as well as temperature, humidity amount and their transport?

We agree with the reviewer that the 13 years of cloud observations should be used in order to study the interannual variability more in detail. We performed a short analysis by looking at weekly average of temperature, moisture, transport of humidity and moist static energy against low cloud cover, mainly for the period before the spring cloud onset to understand what could trigger an earlier spring cloud onset.

The Figure below emphasize (i) the strong relationship (correlation coefficient over XX) between temperature and the low cloud cover over the sea-ice (panel a). For a given week in March, warmer years are consistently cloudier, supporting our interpretation that temperature (via phase partitioning) is a primary control on low-cloud occurrence. (ii) In contrast, while moisture is generally sufficient to allow cloud formation in March on average, year-to-year variations in moisture content and poleward moisture transport still covary with low-cloud cover (panel b and c,  $R(\text{TCWV})=0.9$ , moisture flux  $R(\text{flux})=0.6$ ), indicating that dynamics can modulate cloudiness interannually even if they do not set the seasonal timing of the spring transition.

We added the figure below in the Supplementary materials and added comments on the interannual variability L430 and L454

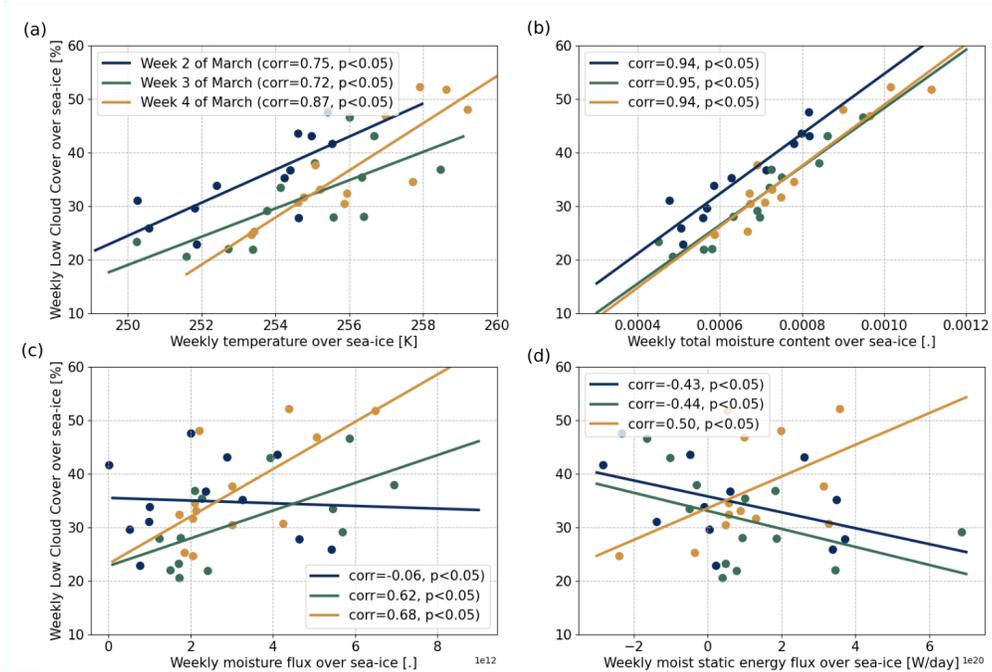


Figure 1: Relationship between weekly average low cloud cover over sea-ice and (a) lower troposphere air temperature, (b) moisture content, (c) poleward moisture flux and (d) poleward moist static energy flux.

- A second point is that the authors should investigate (in link with the interannual variability of cloud occurrences mentioned above) additional parameters influencing cloud occurrence variability. For example, since the study focuses on low clouds, it is important to examine their coupling with the surface. In addition, the link of cloud occurrence with warm air intrusions should be analyzed, including back trajectories to assess air mass transport.

We agree with the reviewer that to investigate the daily variability of cloudiness over sea-ice, an approach looking at air-mass transformation for single moisture intrusion events would be of high interest. However, the objective of this manuscript is different as we focus on explaining the consistent, pan-Arctic seasonal transition in low-level cloudiness, rather than diagnosing the mechanisms controlling individual events. For this purpose, we consider that quantifying (1) the seasonal evolution of large-scale moisture transport into the sea-ice domain and (2) the temperature control on cloud phase provides a relevant explanation for the observed seasonal increase in optically thicker, liquid-containing low clouds. Processes such as surface coupling/decoupling, aerosol–cloud interactions, and event-scale air-mass transformation are certainly important, but beyond the scope of the present seasonal-attribution analysis. We now clarify this scope in the manuscript and highlight event-based air-mass transformation as a direction for future work (L434-436).

- Finally, the present study considers the entire sea ice covered surface only. This area is very large, and figure 1 suggests that the increase in cloud occurrence is more pronounced in certain regions (for example near open oceans: Barents, Kara and Chukchi seas). Therefore, an analysis of the spatial variability of cloud occurrence in specific representative regions with different environmental conditions would be valuable. This could also include areas over open ocean or land, which present highly contrasting conditions in terms of temperature and humidity.

The primary scope of this study is to identify the processes that control the surface energy budget of sea ice during the spring transition, and thus to understand mechanisms directly relevant for sea-ice evolution. Therefore, we decide not to study more in details the spring cloud onset over the open water regions.

The regional discrepancies in spring cloud onset over sea-ice and the links to synoptic conditions are the focus of a full independent separate manuscript submitted in September 2025 currently under review.

### 3 Minor comments

- L 30 : “depending on definition of melt onset”: please give a brief summary of the commonly used definitions.

We agree with the reviewer and added information L34.

- L90 : Please explain how cloud properties could be influenced by boundary-layer processes.

We added one example of how boundary-layer processes can influence cloud properties L90.

- L 98: Please indicate the units of ATB.

We agree with the reviewer and added the unit L128.

- L 106-107: Multilayers clouds are also present. How are you sure that these unclassified are composed of liquid and not ice?

It is true we cannot state that the unclassified layers are ice only, and therefore we analyze it throughout the study as a probable hypothesis. Nevertheless, this hypothesis was further investigated by Cesana et al., (2016) using aircraft measurements, showing that it is likely that ice layers are overrepresented in the unclassified case over the Arctic.

- L 116: Why figure 6 is mentioned before fig 3, 4 and 5 ?

We agree with the reviewer and decided to remove this reference (L150-155)

- L118-122: As the authors explain that unclassified layers are clouds, why these layers are not taking into account in the cloud phase ratio?

We agree with the reviewer that it was not clear enough that we also computed the cloud (ice) phase ratio by considering unclassified cloud phase layers as ice layers in Fig.7. We added additional content in the Data section (L157)

- L118: You should change “cloud phase ratio” into “Ice phase ratio” or something else referring to “ice phase”, according to its definition. It will be more convenient to interpret.

We agree with the reviewer that ”cloud phase ratio” was confusing and changed all instances for ”ice phase ratio”.

- L132: The limit for low-level thick clouds (or ice cloud ratio) in terms of SR is not very pronounced in the figure 3 ( or in figure D1). Could you explain why you used the value of  $SR = 30$  as a threshold? Would using another value significantly change the results?

The value of  $SR = 30$  was chosen based on visual inspection of the evolution of the SR-altitude histograms. We added now Fig.3 these histograms averaged over 2-week periods to emphasize on the increase of this low-level optically thick white box (top panels). Looking at it, we can conclude that choosing another threshold would not critically change the results. The method was also clarified L174-180.

- L127-136: Please, explain with more arguments the interest of the histogram and the two categories you highlight?

The SR–altitude histograms are used to illustrate how the vertical distribution and optical thickness of 480m atmospheric layers evolve from March to May. In particular, they highlight two categories that are central to our interpretation. (1) The low-level optically thick category emphasizes the spring transition toward more opaque low clouds (2) The “probable thin ice” category emphasizes that CALIPSO detects frequent thin ice layers below the standard GOCCP cloud threshold. These layers are not included in the ice-cloud fraction based on ( $SR > 5$ ), but are consistent with the frequent presence of atmospheric ice particles (with Ice Water Content below the approximate CALIPSO-GOCCP detection limit of  $2.5 \times 10^{-3} g.m^{-3}$ ). We added these explanations L174-180.

- L162-167: There was some confusion when reading this section. I understand that CALIPSO-GOCCP may miss some thin ice clouds when  $SR < 5$  and you use the ground based observations for ensure that ice clouds could be detected when  $SR > 3$ . But, how can you be sure that the satellite and ground based lidars have the same cloud sensitivity? Could you for example provide the frequency distributions of the SR for the two systems (co-located along the MOSAIC track)?

We agree with the reviewer that the sensitivity of both lidars might be different. However, we cannot provide a quantitative comparison as the MOSAiC campaign was located in the North Pole blind zone of CALIPSO (over 81°N). Nevertheless, the motivation is not only set using observations by the MOSAiC lidar but also on the study by Lacour et al., 2017 showing that CALIPSO-GOCCP threshold do not allow to capture thin ice particles in the Arctic. This study was performed by doing quantitative comparison of Scattering Ratio with ground-based lidar (Summit Station).

- Figure C1: I see more clouds for SR between 1 and 3 on the figure ? You wrote the opposite in the text? This figure need more explanation, and you could add it in the manuscript.

Fig.C1 indicate that moving the SR threshold for cloud detection from 1 to 3 does not modify the ice cloud fraction. This means that no "objects" are detected between these two values of scattering ratios. While between 3 and 5, the ice cloud fraction decreases drastically, meaning that most of the ice clouds are detected in the SR range of 3 to 5. We modified Fig.C1 caption and expect the figure to be more redeable now.

- L183: "To understand low cloud formation.....humidity and temperature." Other parameters may impact the cloud formation, such as dynamics, surface coupling, stability, local sources or long range transport of aerosols... (see my major comment above)

We refer here to our answer for the second general comment.

- Section 2.1: I suggest to include open seas and MIZ areas. (see the major comment)

We thank the reviewer and answered this in the major comments section.

- L260-262: "Moreover...relative to March". This sentence is unclear. Please, rewrite.

We agree with the reviewer and modified L328-330 to make the point clearer.

- L265-280: For the blocking event, could you provide maps similar to figure F1 to identify the moisture decrease? In addition, do you have hypothesis for this cloud occurrence increase since it is not due to moisture advection ? A more detailed meteorological analysis of the situation would be helpful. Back trajectories could provide useful insights insight into air mass transport, and give an indication of aerosol transport. Moreover, this section well illustrates that cloud occurrences and moisture transport can vary substantially on a daily scale, and that this variability has to be considered, in addition to the annual averages presented in the paper.

We thank the reviewer for pointing out this omission and have added Fig. F2. We agree that synoptic-scale conditions can strongly influence Arctic cloud cover on daily timescales, superimposed on the seasonal cycle discussed here. We now emphasize the importance of investigating this daily variability further in the conclusion (L435).

- Figure 4: Blue light curves not really visible. Please improve.

We thank the reviewer for this review and modified Fig.4.

- L 284: "from" missing between "observations" and "Andreas et al"

We agree with the reviewer and modified L351.

- L 319: How does figure 7b change if you use only the cloud layer to determine the temperature distributions?

We provide a comparison of the Fig.7b temperature distributions computed using (i) all atmospheric layers and (ii) cloudy layers only. As expected, restricting the sample to cloudy layers shifts the distribution toward warmer temperatures. The shift is largest in April, which we interpret as reflecting

the greater contribution of cloudy layers in late April compared to early April, when temperatures are also warmer. We did not include this additional figure in the revised manuscript.

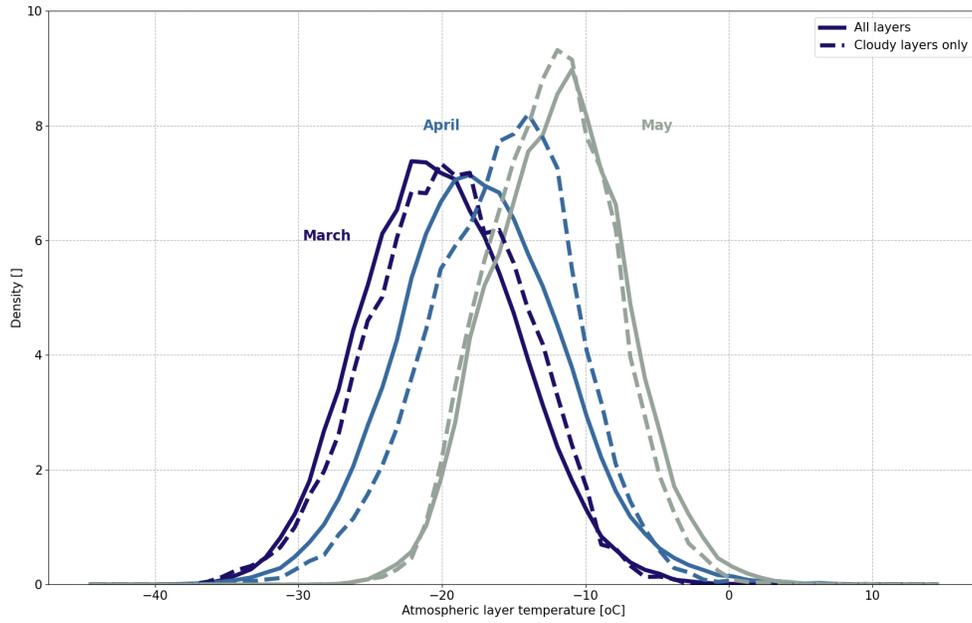


Figure 2: Temperature probability density function by considering all atmospheric layer as done originally in Fig.7 of the paper or considering cloudy layers only.