



Regional and Seasonal Distribution of Arctic Low-Level Cloud Types and Their Relationship to Large-Scale Environmental Conditions

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Abstract. Low-level clouds strongly influence the Arctic surface energy budget and hydrological cycle, yet their representation in climate models remains challenging due to limited observations and complex interactions between local processes and large-scale conditions. This study analyzes eight years (2007–2016) of active remote sensing observations from CALIPSO and CloudSat to investigate the regional and seasonal distribution of four types of low-level clouds: warm liquid, ice-only, mixed-phase clouds (MPCs), and unglaciated supercooled liquid clouds (USLCs). 51 % of Arctic clouds occur below 3 km. The statistical analysis of cloud-type frequencies shows that MPCs account for 17 %, ice-only clouds for 21 %, and USLCs for 12 %. This study provides the first satellite-based assessment of USLCs over the Arctic, revealing occurrences up to 20 % over marine regions during transition seasons. Multiple linear regressions are used to quantify the influence of key environmental drivers on the cloud type distribution. MPCs are linked to dynamically unstable conditions such as marine cold-air outbreaks, especially over open sea regions and during transition seasons. USLCs preferentially develop under stable and relatively dry mid-tropospheric environments as opposed to ice clouds. Cloud–surface coupling shows that, on average, 32 % of low-level clouds are coupled to the surface. In winter, USLCs are four times more frequently coupled with the open ocean than with sea ice, emphasizing the strong thermodynamic control of the underlying surface. These results provide new insight into Arctic cloud-phase variability and offer guidance for improving their representation in large-scale models.

1 Introduction

Low-level clouds are ubiquitous in most regions of the Arctic (De Boer et al., 2009; Philipp et al., 2020; Taylor and Monroe, 2023; Wendisch et al., 2023a; Jiang et al., 2024). These clouds exert a strong influence on the surface energy budget, with an annual warming effect (Raschke et al., 2016; Li et al., 2023). The radiative effect of low-level clouds (CRE) evolves strongly over time, yet differently if they are formed above the open ocean, sea ice-covered, or continental regions (Intrieri and al., 2002; Miller et al., 2015; Ebell et al., 2020; Yan et al., 2020; Cesana et al., 2024). Estimates of the CRE of low-level clouds, related



to their seasonal and regional variabilities, remain highly uncertain as illustrated by the difficulties in simulating observations using actual models (Lenaerts et al., 2017; Sedlar et al., 2020; Li et al., 2023; Griesche et al., 2024).

Local to large scale models struggle to simulate basic properties such as the cloud cover and thermodynamic phase distribution in the Arctic (Prenni et al., 2007; De Boer et al., 2014; Komurcu et al., 2014; Cesana et al., 2015; McCoy et al., 2016; Pithan et al., 2016). In particular, climate models tend to underestimate the amount of liquid-containing clouds, which in turn leads to inaccurate estimates and variability of the CRE and precipitation (Tjernström et al., 2008; Vavrus et al., 2009; Cesana et al., 2012; Kay et al., 2016; McIlhattan et al., 2017). The discrepancy between model outputs and observations may be due to our lack of understanding of the complex processes involved in the formation of different cloud phases (droplets, crystals and supercooled droplets) and their interplay with thermodynamical conditions, but also due to the difficulty in providing accurate and statistically representative observations of these different cloud phases. Modelling studies have shown that oversimplified or inaccurate parameterizations of microphysical processes (nucleation of ice crystals and droplet-ice interactions) and phase partitioning lead to an overestimation of the freezing of water droplets at low temperatures and therefore of the liquid water fraction (Avramov et al., 2011; Ovchinnikov et al., 2014; Tan and Storelvmo, 2019). More recently, Raillard et al. (2024) confirmed that the commonly used temperature-dependent phase partitioning in climate model cloud schemes is inappropriate to sustain liquid droplets at low temperatures and therefore cannot accurately simulate Arctic mixed-phase clouds (MPCs). The life cycle of these low-level clouds results from complex interactions between local microphysical, radiative, dynamical processes and larger scale environmental conditions (Morrison et al., 2012; Li et al., 2020a, b; Griesche et al., 2021). A better understanding of these processes and a better quantification of the radiative impact of clouds in the Arctic requires an accurate determination of their macrophysical and of the vertical structure of the microphysical properties.

Statistics of ground-based and, to a lesser extent, airborne observations helped to characterize Arctic low-level cloud properties. They have highlighted the high occurrence of low-level clouds and the persistence of liquid-containing clouds, which have a large impact on the surface energy budget (Dong et al., 2010; Shupe et al., 2011; Nomokonova et al., 2019). These studies contributed to our understanding of the physical processes involved in the life cycle of low-level clouds via case studies, but they cannot be extrapolated over the entire Arctic domain. Long-term satellite observations of the regional and seasonal distribution of low-level cloud types are therefore crucial to reduce the spread between large scale models on the annual cycle of the cloud fraction and cloud phase (Lenaerts et al., 2017; Taylor et al., 2019). Studies based on satellite observations have shown pronounced inter-regional and seasonal variations of the low-level cloud occurrence (Lelli et al., 2023; Jiang et al., 2024), yet with a lack of coherence, especially regarding the retrieval of the cloud phase. Passive remote sensing observations have well-known limitations in the Arctic, leading to an underestimation of the low-level and mixed-phase cloud fraction (Schweiger and Key, 1992; Chan and Comiso, 2013; Philipp et al., 2020). Satellite products based on active remote sensing observations of the vertical structure of clouds improved the characterization of the distribution of the cloud phase in the Arctic (Cesana et al., 2012; Mioche et al., 2015; Matus and L'Ecuyer, 2017; Cesana et al., 2024).

However, disagreements persist when comparing basic properties such as the occurrence of the thermodynamic phase of low-level clouds with active instruments. This is partly due to the ability of the instruments (lidar and radar) used to detect the peculiar microphysical structure of low-level MPCs, which generally consist of an upper layer dominated by supercooled water



droplets and lower layers containing ice crystals (Shupe et al., 2006; McFarquhar et al., 2007; Mioche et al., 2017; Moser et al., 2023). Because the lidar cannot penetrate most of the optically thick liquid-topped layers, studies relying on the lidar alone tend to combine real MPCs and liquid-only clouds into a single liquid-containing cloud type. Cloud phase retrievals based on algorithms that exploit the lidar-radar synergy can reduce these biases, but they are also confronted with the observational scale-dependent definition of a mixed-phase cloud. Indeed, in most of the studies clouds are considered to be in the mixed phase regime only if both liquid droplets and ice crystals are detected in the same cloud layer or pixel. This assumption is expected to lead to an underestimation of the MPCs occurrence as these clouds are often characterized by successive single phase layers and only one layer can be detected by a single instrument. Therefore, as a first step it is important to more accurately assess the frequency of occurrence of different low-level cloud types related to their thermodynamic phase. In addition to ice clouds and warm liquid clouds, a segregation between MPCs and unglaciated supercooled liquid clouds (USLCs) is necessary, but has been lacking in previous studies. These two latter types of clouds result from different microphysical processes and are likely to be influenced by different large-scale conditions. In a warmer and wetter Arctic setting, the cloud-type regional and seasonal distributions are expected to change and long term observations of cloud vertical profiles are needed to monitor and capture possible modifications of the Arctic cloudiness.

Spaceborne cloud phase observations combined with regional reanalyses can be exploited to identify factors influencing the distribution of cloud types at larger spatial and temporal scales. Previous studies have shown that lower tropospheric stability (LTS), the vertical structure of temperature and humidity, moisture inversions, air mass intrusions, long-range transport of aerosols and surface type are amongst the main factors controlling the low-level cloud cover (Sedlar et al., 2012; Coopman et al., 2018; Knudsen et al., 2018; Pithan et al., 2018; Eirund et al., 2019). For instance, Yu et al. (2019) showed that strong LTS over open ocean tends to increase the cloud cover and the amount of liquid water, whereas the opposite trend seems to be observed over sea ice (Taylor et al., 2015). The large-scale advection of moisture and heat often associated with phenomena such as warm air intrusions (WAI) or cold air outbreaks (CAO) from higher or lower latitudes can also induce rapid changes in local weather conditions and directly affect the formation and structure of low-level clouds (Lackner et al., 2023). Moisture intrusions over the boundary layer are usually associated with increased cloudiness (Persson et al., 2017; Messori et al., 2018) and tend to promote larger liquid water content (Eirund et al., 2019). However, during WAI over the oceanic boundary layer, there seems to be no consensus on its impact on low-level cloud microphysical properties and coverage. Some studies show a decrease in cloud fraction and liquid water content (Knudsen et al., 2018; Eirund et al., 2019) while in situ observations point towards an increase in number and mass concentrations of liquid water droplets (Mioche et al., 2017; Moser et al., 2023). The underlying surface and whether the cloud is coupled or decoupled from the surface, as well as the large-scale transport of aerosol particles, also modify the microphysical properties and the thermodynamic phase of low-level clouds (Kay and Gettelman, 2009; Bossioli et al., 2021; Schmale et al., 2021; Raut et al., 2022; Moser et al., 2023). In general, the regional variability of these environmental factors is not well represented in climate models which impacts the simulation of the distribution of the low-level cloud properties in the Arctic (Barton et al., 2014; Cesana et al., 2015; McCoy et al., 2016; Tan et al., 2016).



Moreover, in the context of significant changes in this region of the globe, low-level cloud fractions and types may be affected by changes in large-scale environmental conditions (Kay and Gettelman, 2009; Eastman and Warren, 2010; Liu et al., 2017; Morrison et al., 2019; Liu and Schweiger, 2024). To improve our understanding of how these conditions influence the properties of low-level clouds and to reduce model biases, we argue that more accurate estimates of the frequency of occurrence of phase-related cloud types are necessary in different regions of the Arctic. The first objective of this study is to provide representative and longer-term statistics on the regional and seasonal distribution of low-level warm liquid, ice only and mixed-phase clouds as well as the overlooked unglaciated supercooled liquid clouds. The second objective of this study is to identify a first set of basic environmental parameters that impact the geographical distribution of cloud-type occurrence at a large scale. Statistical analyses of the relationship between cloud-type cover and these parameters provide insight into which are the most influential parameters on the low-level cloud cover at a regional scale. This data set and its associated analyses can be used to evaluate the output of climate and regional models, provide guidance on improving cloud phase parameterization, and facilitate future comparisons with Earth Clouds, Aerosols and Radiation Explorer (EarthCARE; Illingworth et al., 2015) observations of cloud distribution in the Arctic.

We rely on the synergy of CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) and CloudSat radar satellite measurements (DARDAR-MASK products, Delanoë and Hogan, 2008, 2010; Ceccaldi et al., 2013) collocated with thermodynamic variables from ECMWF (European Centre for Medium-Range Weather Forecasts) analyses, sea ice concentration and aerosol loading, to analyze 8 years of cloudy scenes over different Arctic regions. DARDAR (raDAR–liDAR) products, combined with the cloud classification algorithm, are used to determine the occurrence of the thermodynamic phase of low-level clouds. Section 2 describes the dataset, the DARDAR classification algorithm, and the statistical analyzes used to characterize cloud-type occurrences. The uncertainties and limitations associated with this methodology are also discussed. Section 3 presents the results on the spatial distribution and temporal variations of cloud-type occurrences. Multiple linear regressions (MLR) are also implemented to quantify the influence of key environmental parameters on cloud occurrences. In particular, we identify the dominant parameters driving each cloud type and examine their relationship with cloud–surface coupling. Section 4 summarizes our main results and discusses them in relation to previous studies.

2 Methods and Data

2.1 DARDAR products and cloud-type classification

In this study, we investigate the variability of the occurrence of low-level clouds (500 to 3000 m above ground level) in the Arctic (60°N–82°N) between 2007 and 2016 using the DARDAR-MASK v2.23 product (Delanoë and Hogan, 2008, 2010; Ceccaldi et al., 2013). In this satellite product the vertical profiles of the 532 nm attenuated backscatter coefficient measured by the CALIOP lidar onboard CALIPSO (McGill et al., 2007; Winker et al., 2007) are merged with the 94 GHz (W-band) reflectivity profiles from the Cloud Profiling Radar (CPR) onboard CloudSat (Stephens et al., 2002) on the same resolution grid. Since the lidar signal is more sensitive to the cloud optical extinction and the radar reflectivity to the size of large cloud particles (ice crystals), the combination of both measurements is used to detect the hydrometeor type (or phase) within a cloud



layer. Therefore, the DARDAR-MASK v2.23 product provides a vertically resolved classification of the cloud hydrometeor type and aerosols (see Figure S1 in the Supplement) along the A-Train track, with each atmospheric pixel ($60 \text{ m} \times 1.7 \text{ km}$) assigned to one of 18 classes (Ceccaldi et al., 2013). These classes include clear sky, aerosols, stratospheric features, and several categories of hydrometeors.

Warm liquid water pixels are identified by strong lidar attenuation ($\beta_{532} \geq 2 \cdot 10^{-5} \text{ m}^{-1} \text{ sr}^{-1}$) at temperatures above 0°C . Supercooled liquid water pixels are defined by subfreezing temperatures ($-40^\circ \text{C} < T < 0^\circ \text{C}$), along with strong lidar attenuation, and for a layer thickness lower than 360 m. Mixed-phase pixels are characterized by a strong lidar attenuation caused by supercooled liquid droplets combined with the presence of ice crystals detected by the radar reflectivity signal. All remaining cloudy pixels at below freezing temperatures correspond to ice-only pixels ($\beta_{532} < 2 \cdot 10^{-5} \text{ m}^{-1} \text{ sr}^{-1}$, no strong lidar attenuation and/or radar detection signal). It should be noted that the lidar signal can be rapidly attenuated in clouds with an optical depth greater than 3 to 5, depending on their microphysical composition (Chepfer et al., 2014). If the signal is extinguished or fully attenuated, the underlying cloud pixel phase diagnosis relies only on the radar reflectivity. This could lead to an underestimation of pixels classified as liquid or mixed-phase. Backscattering signals can also be contaminated by ground echoes (surface clutter or false ground detection), which could induce misclassifications of pixels located close to the surface (Marchand et al., 2008). Maahn et al. (2014) and Schirmacher et al. (2023) showed that the depth of the CloudSat blind zone was strongly dependent on the type of surface with a narrower zone over ocean and sea ice, but reaching up to 1.2 km over land. It should also be noted that specific DARDAR-MASK classes are designed to identify potential clutter contamination (class -1: surface and subsurface), thereby limiting misclassification in these lower atmospheric layers. Comparing of DARDAR-MASK products with ground-based observations (Mioche et al., 2015) showed that selecting data corresponding to altitudes higher than 500 m was a good compromise to minimize statistical biases and ensure a significant fraction of valid pixels in the lower troposphere. DARDAR-MASK pixel classification issues were also reported by Mioche and Jourdan (2018). Comparisons with co-located in situ observations in low-level Arctic clouds showed that the liquid or the ice phases were accurately diagnosed by DARDAR-MASK 90 % of the time, in single phase clouds. However, in situ measurements revealed that almost 50 % of the DARDAR-MASK "ice" pixels within boundary layer mixed-phase clouds were actually a mixture of supercooled water droplets and ice crystals. The main sources of disagreement were attributed to the full attenuation of the lidar signal by the upper cloud layers and the contamination of near-surface pixels by radar ground echo.

To mitigate these limitations, we used the DARDAR classification program to estimate the occurrence of four distinct types of clouds. This program was originally developed for Arctic clouds by Mioche et al. (2015) and later updated and extended by Bazantay et al. (2024) to study low-level clouds over the Southern Ocean, hence the name DARDAR-SOCP (DARDAR for Southern Ocean Cloud Phase). The algorithm analyzes the vertical structure of each atmospheric column to extract the cloud composition between 500 and 3000 m. The atmospheric column sampled is divided into "pixels" with a vertical resolution of 60 m, which are all assigned to a specific DARDAR-MASK class value. A cloud is defined as at least three vertically adjacent cloudy pixels (180 m), in accordance with in situ observations of low-level clouds (Mioche et al., 2017; Achtert et al., 2020; Järvinen et al., 2023; Moser et al., 2023; Zanatta et al., 2023). A single column may contain several distinct cloud



layers, provided that they are separated by at least three clear-sky pixels. Accordingly, four categories of low-level clouds are distinguished:

- Warm clouds: consisting exclusively of liquid water droplets at $T > 0^\circ\text{C}$.
- 160 – Cold clouds: including all cloud types with temperatures below 0°C , i.e., all clouds except warm clouds.
- Ice clouds: composed entirely of pixels of ice crystals.
- Unglaciaded supercooled liquid clouds (USLCs): composed solely of supercooled liquid water droplet pixels.
- Mixed-phase clouds (MPCs): characterized by a mixture of pixels of different phases (i.e., pixels of liquid water droplets and pixels of ice crystals and/or droplets and crystals in the same pixel).

165 In DARDAR-SOCP, the requirement of at least three consecutive cloudy pixels to define a cloud can bias the detection of mixed-phase clouds, which often consist of successive single-phase layers. As a result, the occurrence of MPCs can be overestimated compared to the occurrence of ice and liquid clouds. We showed that these cloud-type classification biases can lead to uncertainties in the cloud occurrence of 15 % for ice, 20 % for liquid, and 10 % for mixed-phase clouds (see Supporting Information of Bazantay et al., 2024). A potential underestimation of liquid phase may also occur as a result of lidar signal
 170 attenuation by an overlying liquid water layer located above 3000 m. The cloud occurrence for each type (OC_n) is calculated as the ratio of the number of observations of that type (N_n) to the total number of satellite footprints ($N_{footprint}$), expressed as a percentage:

$$OC_n = \frac{N_n}{N_{footprint}} \times 100 \quad (1)$$

Cloud occurrences are computed for each cloud type on the basis of 7-day satellite data averages, ensuring statistical ro-
 175 bustness at a regional scale. All footprints located between 60°N and 82°N (14 overpasses per day in the Arctic region) are processed and aggregated into $2^\circ \times 2^\circ$ latitude–longitude boxes. The years 2011 and 2012 are excluded due to an anomaly in the CloudSat battery, which caused a loss of data. Before 2010, both daytime and nighttime observations were used, while after 2012, only daytime observations were considered in our study because of the same battery-related issues. Relying only on CloudSat’s daylight operations mode (2013–2016) led to fewer observations, particularly during winter and at high latitudes
 180 (Kotarba and Solecki, 2021). This limitation introduces a seasonal bias in cloud climatologies, with a slight overestimation of winter occurrences ($\approx 3\%$), especially over oceans (Noel et al., 2018). More details are provided in the Supplement (see Figures S2, S3, and Text S1).

2.2 Selection of environmental factors

Thermodynamic data are used to analyze the impact of environmental conditions on cloud occurrence and type. DARDAR-
 185 SOCP retrieves thermodynamic variables from ECMWF analyzes, which are integrated into DARDAR-MASK files as part



of the ECMWF-AUX collocated products (Delanoë et al., 2011; Hersbach et al., 2020). ECMWF-AUX is an intermediate product in which the 3h thermodynamic property forecasts of the ECMWF model on a $0.5^\circ \times 0.5^\circ$ grid are interpolated to each CPR radar profile (Cronk and Partain, 2017). The set of parameters used in this study is summarized in Table 1. In addition, three metrics are calculated to characterize the vertical structure of the lower troposphere and the advection of heat and moisture at a regional scale: Lower-Tropospheric Stability ($LTS = \theta_{700hPa} - \theta_{1000hPa}$, Wood and Bretherton, 2006), Estimated Inversion Strength ($EIS = \theta_{700hPa} - \theta_{surf} - \Gamma_m^{850hPa}(Z_{700} - LCL)$, Wood and Bretherton, 2006) and Marine Cold Air Outbreak ($MCAO = \theta_{surf} - \theta_{800hPa}$, Fletcher et al., 2016). Here, θ denotes the potential temperature (K), and the subscripts (e.g., surface, 700hPa, 1000hPa) indicate the pressure levels at which it is evaluated. Γ_m^{850hPa} is the moist-adiabatic lapse rate at 850 hPa, Z_{700} is the geopotential height at 700 hPa, and LCL refers to the lifting condensation level height.

Table 1. List of the environmental parameters.

Data source	Parameters	Level / Index	Initial resolution	Unit
ECMWF-AUX	Temperature (Temp)	Surface, 850 and 700 hPa	3 h, 0.5°	K
	Wind	Surface, 850 and 700 hPa	3 h, 0.5°	$m.s^{-1}$
	Pressure (Press)	Surface	3 h, 0.5°	hPa
	Sea surface temperature (SST)	Surface	3 h, 0.5°	K
	Specific humidity (SH)	850 and 700 hPa	3 h, 0.5°	$g.kg^{-1}$
	Geopotential height (GH)	850 and 700 hPa	3 h, 0.5°	m
	Integrated water vapor (IWV)	Column	3 h, 0.5°	$kg.m^{-2}$
	Lower-Tropospheric Stability (LTS)	Stability index	3 h, 0.5°	K
	Estimated Inversion Strength (EIS)	Stability index	3 h, 0.5°	K
	Marine Cold Air Outbreak (MCAO)	Air-mass index	3 h, 0.5°	K
AMSR-E / AMSR2	Sea ice concentration (SIC)	Surface	daily, 6.25 km	%
CALIPSO	Aerosol Optical Depth (AOD) - 532 nm	Column	sub-daily, 5 km horiz., 60 m vert.	–

In this study, we also account for the type of cloud underlying the surface: land, open ocean, or sea ice. In particular, sea ice concentration (SIC) is used to characterize sea and ocean surface conditions. SIC data are obtained from the AMSR-E instrument on board AQUA (2002–2011) and AMSR2 on board GCOM-W1 (2012–present). Both are passive microwave radiometers that measure brightness temperatures in several channels (18–89 GHz). SIC is retrieved with the ARTIST Sea Ice (ASI) algorithm (Spreen et al., 2008; Du et al., 2017), which has been validated against other retrieval methods and in situ data (Wiebe et al., 2009). The typical uncertainty for 100 % sea ice cover is 5.7 % (Spreen et al., 2008), with higher uncertainties in the marginal ice zone due to mixed ocean/ice pixels and atmospheric contamination.



To investigate the influence of aerosol particles on cloud-type occurrence, we use a CALIPSO product (“01kmCLay.v4.20”, Young and Vaughan, 2009), of aerosol optical depth (AOD). AOD can be regarded as a first order indicator of aerosol loading in the atmosphere. Aerosol profiles are generated with a vertical resolution of 60 m and a horizontal resolution of 5 km in the troposphere. AOD at 532 nm is derived from the extinction profiles associated with each granule collocated to DARDAR data. A cloud–aerosol discrimination score (CAD, Liu et al., 2009, 2019) is used to separate aerosols from clouds, with more than 90 % of detected layers having a confidence level above 70 %. The uncertainty in AOD arises mainly from the assumed lidar ratio: it is about 50 % for $AOD \approx 0.5$ and increases with optical thickness. In this study, AOD is used as a tracer of aerosol load in the atmosphere, providing a proxy for aerosol effects on cloud occurrence and phase.

The selection of this limited set of environmental factors is consistent with previous studies carried out in mid-latitudes (Scott et al., 2020; Naud et al., 2023) and in the Arctic (Morrison et al., 2012; Kay et al., 2016; Liu et al., 2017; Yu et al., 2019). The environmental parameters are averaged over 7 days and collocated on a $2^\circ \times 2^\circ$ grid to match the temporal and spatial resolution used for cloud-type occurrences. This weekly averaging ensures statistical robustness and avoids biases associated with the sparse daily coverage of individual orbits. The environmental parameters are partitioned in the same way as cloud-type occurrences to ensure temporal consistency. Moreover, the week-long timescale remains well suited to capture synoptic variability (MCAO), which typically evolves over several days. This timescale is thus appropriate both to obtain representative cloud-type occurrences and to investigate the variability of environmental parameters at the regional scale.

2.3 Multiple linear regression

In this study, we implement multiple linear regression (MLR) analyzes to identify the environmental factors that contribute the most to the regional and seasonal variability of cloud-type occurrences. This statistical approach is used to predict the variation of a dependent variable (e.g., cloud occurrence) as a linear combination of several explanatory variables (e.g., environmental parameters). It relies on a least-squares estimator to minimize the error between predicted and observed values (Legendre and Legendre, 2012). In this study, we apply MLR to relate several environmental predictors to the target variable (OC_n) as follows:

$$OC_n = \beta_0 + \beta_1 x_1 + \dots + \beta_i x_i + \epsilon \quad (2)$$

where β_0 represents the intercept, β_i the regression coefficients associated with each predictor x_i , and ϵ the residual. MLR variables (x_i) are normalized to ensure a direct comparison of the relative importance of each parameter (Bring, 1994; Grace et al., 2018). We follow the same MLR methodology as in Coopman and Tan (2023), ensuring consistency with recent approaches applied to Arctic cloud studies. Before each regression, we evaluated the multicollinearity between predictors and explanatory variables based on the Variance Inflation Factor (VIF, see Figure S4a in Supplement). According to Liu et al. (2021), variables with a VIF greater than 10 are excluded from multiple linear regression analysis. Non-significant predictors, either showing a p-value greater than 0.05 or exhibiting no clear influence (e.g., wind; see Figure S4b in the Supplement) in the simple correlations with cloud-type occurrences ($R^2 < 0.1$), were excluded to retain only robust explanatory factors for each



cloud type. The relation between the cloud occurrence and the environmental parameters is expected to be nonlinear leading to relatively low R^2 , but it remains satisfactory at the first order with R^2 greater than 0.3. To assess potential dependencies between predictors, we also computed pairwise correlations using Spearman's rank method. The correlation matrix shown in Figure 1 reveals strong links between several environmental variables that are inherently interdependent and are often correlated to varying degrees. This is especially the case for the temperature ($R^2_{Surf_Temp/SST} = 0.85$; Fig. 1) and the humidity variables at different atmospheric levels, as well as for EIS and LTS ($R^2_{EIS/LTS} = 0.94$; Fig. 1).

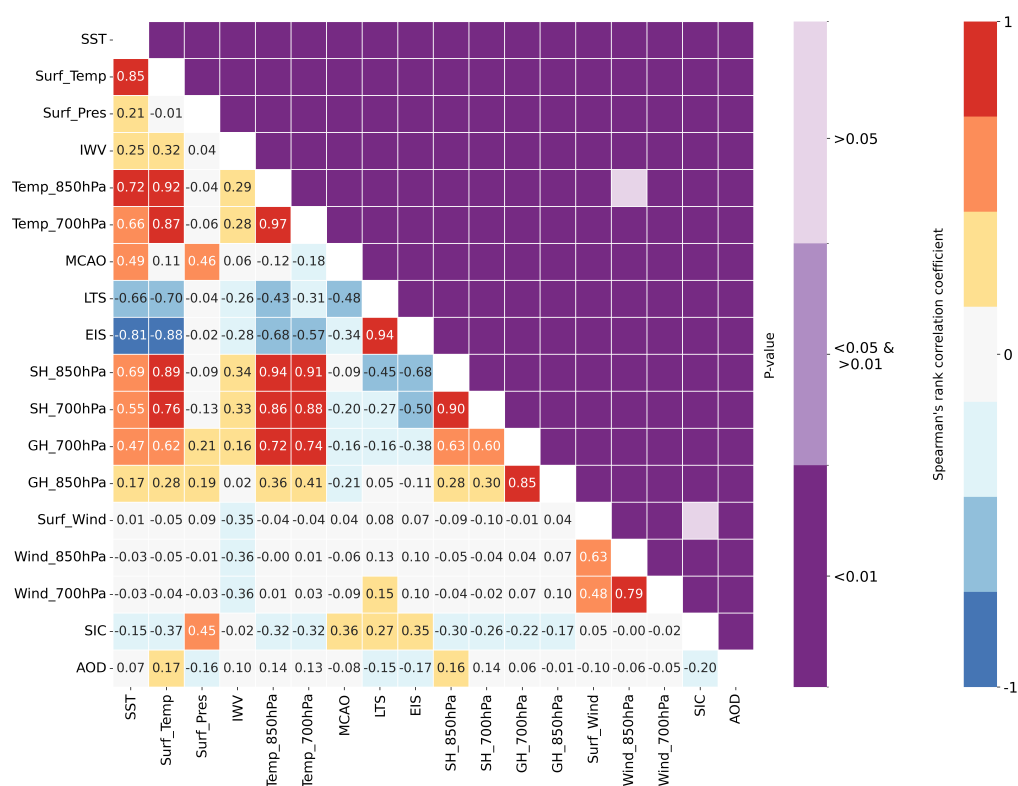


Figure 1. Spearman's rank correlation matrix and associated p-values for each key parameter across all regions.

Accordingly, to minimize the collinearity and redundancy between the different predictors, nine variables are selected for the MLR analyzes: surface temperature (Surf_Temp), surface pressure (Surf_Pres), integrated water vapor (IWV), lower-tropospheric stability (LTS), marine cold air outbreak (MCAO), specific humidity at 700 hPa (SH_700hPa), geopotential height at 850 hPa (SH_850hPa), sea ice concentration (SIC), and aerosol optical depth (AOD). These parameters characterize the basic properties of the lower troposphere thermodynamic structure, the surface conditions and the aerosol loading. We expect this limited set of parameters to be sufficient to statistically investigate how varying environmental conditions impact the regional distribution of low-level clouds.



During the 8-year study period, the observational dataset included in the MLR consists of approximately 680,000 points used in the regressions. To ensure that each regression point is based on a sufficient number of observations, we applied a minimum threshold set to the first quartile of the number of observations at each latitude band. This procedure removes the 25 % least sampled grid cells, which are the least statistically representative, and retains only robust points for the regression. Finally, the dataset is randomly divided into two subsets: 80 % of the data are used to train the MLR models, and the remaining 20 % serve as an independent test set for validation. The performance of the regression model is quantified using standard statistical metrics, including the coefficient of determination (R^2 and adjusted R^2), the root mean square error (RMSE) and the bias of the model. These metrics provide a measure of the precision and robustness of the regressions.

3 Results

3.1 Geographical variability of low-level cloud occurrences

This section examines the distribution of cloud occurrence (OC) in different regions of the Arctic. On average, the analysis of the DARDAR-MASK products shows that clouds are present 69 % of the time throughout the atmospheric column between 0.5 and 12 km. Figure 2 shows the geographical distribution of the occurrence of low-level clouds in the Arctic for the different cloud types : total clouds, cold clouds, warm clouds, ice clouds, USLCs and MPCs. In the Pan-Arctic, we find that the median annual occurrence of low-level clouds (OC_{all-ll}) with heights between 0.5 and 3 km is 50.9 % (Fig. 2a). However, their distribution is highly inhomogeneous across the different Arctic regions. The vast majority of these low-level clouds ($OC_{cold-ll} = 48.8$ % of 50.9 %) evolve in an environment where the cloud temperature is below 0°C referenced as cold clouds (see Fig. 2b). This occurrence decreases at lower latitudes, especially over oceanic regions. Accordingly, even though the median occurrence of warm liquid clouds (OC_{warm}) over the Arctic does not generally exceed 3 % (Fig. 2c). The average distribution of fully glaciated cloud occurrences (OC_{ice}) shows geographical contrasts. OC_{ice} median value is 20.2 % over the Arctic but can reach 30-35 % in the continental and mountainous regions of Siberia, Alaska and Greenland (Fig. 2d). Figure 2e shows that clouds composed exclusively of supercooled water droplets (USCLs) are less common than ice clouds, with a median occurrence of around 11.6 % (OC_{USLCs}). Finally, mixed-phase clouds, which are characterized by a mixture of water droplets and ice crystals, are observed on average 17.0 % of the time over the Arctic (Fig. 2f). The geographical variability of these two types of liquid-containing clouds is also pronounced. MPCs prevail over regions influenced by the North Atlantic Ocean and the Bering Sea ($OC_{MPCs} > 30$ %).

Based on the spatial distribution of the cloud-type occurrence, on the main weather patterns (high- and low-pressure systems) and geographical limits (latitudes, oceans, continents), we choose to subdivide the Arctic into 12 distinct subregions (Fig. 3a). The six subregions in Zone 1 have latitudes ranging from 60°N to 70°N, whereas the northernmost regions are located within the high-latitude ring which extends from 70°N to 82°N (Zone 2). Subregions 1B and 2B, as well as 1C and 2C, are merged to increase the statistical significance of the results (1-2B and 1-2C). The purpose of this regionalization is to highlight the specific features of the low-level cloud occurrence in the Arctic. A statistical analysis of total cloud occurrences for each region is presented in Figure S5 and discussed in Text S2 of the Supplement.

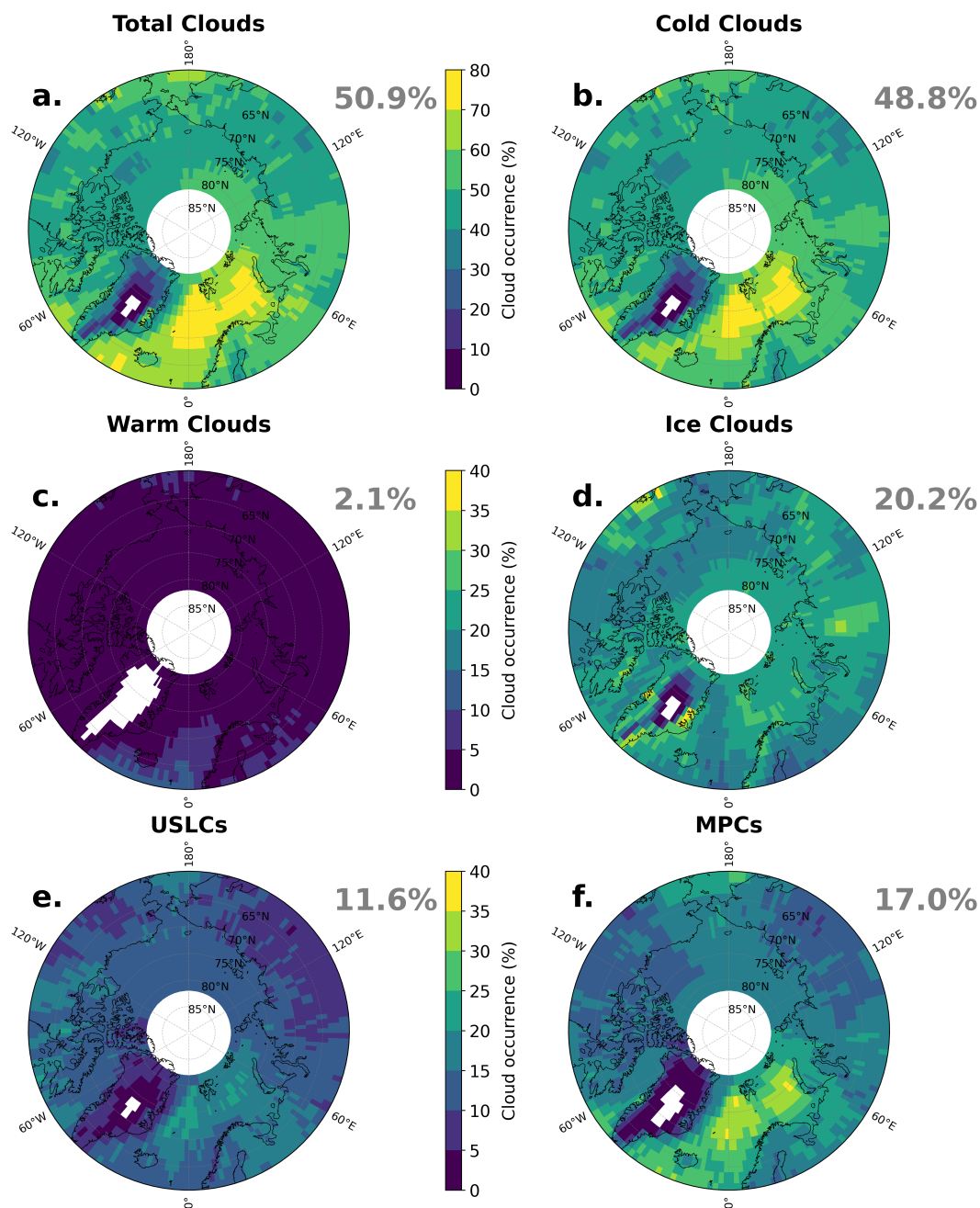


Figure 2. Stereographic projections of the occurrence of low-level (0.5-3 km) cloud types between 2007 and 2016: (a) total clouds, (b) cold clouds, (c) warm clouds, (d) ice clouds, (e) USLCs, and (f) MPCs. The number in the upper right of each subfigure represents the median occurrence for the entire study area.



280 The northeast Atlantic sector (region 1A) is the area with the highest occurrence of warm clouds ($\approx 10 - 15\%$). MPCs are also frequent in this region, as well as over the seas surrounding the Svalbard Archipelago (region 2A), where they occur up to 35 % of the time. These two regions are influenced by the Gulf Stream and low-pressure systems. They are characterized by the highest low-level cloud occurrence ($OC_{all-l} > 60\%$). A specific feature of region 2A is the prevalence of MPCs and USCLs over the Greenland, Barents, and Norwegian Seas (OC_{USLCs} with peaks around 25 %). The lowest low-level cloud cover is found in Greenland (1-2B) although a non-negligible occurrence of ice clouds is observed near the shores. However, the complex terrain and topography of this region undermine the reliability of our results (narrower column analyzed, larger radar ground echo). Low-level ice clouds are more prevalent in mountainous regions of Alaska and western Canada (1E) ($OC_{ice} > 25\%$) than in eastern provinces of Canada (1D) and, to a lesser extent, than in the Labrador Sea and Baffin Bay (1-2C). In these latter regions and parts of eastern Europe (1H), USLCs occur more frequently than in continental areas with relief of western Canada (1E) and central and eastern Russia (1G), for which OC_{USLCs} is lower than 10 %. The cloud-type cover over the Bering Sea sector (1F) differs from that in neighboring regions. The frequency of occurrence of low-level clouds, and of liquid-containing clouds in particular, is much higher ($OC_{MPCs} = 25\%$ and $OC_{USLCs} > 15\%$) than in surrounding regions subject to high-pressure systems. The northernmost eastern sector of the Arctic (2F) is more cloudy ($OC_{all-l} = 55\%$) than the Beaufort and Chukchi Seas (2E) and the northern Nunavut region of Canada (2D). Region 2E experiences a 5 % higher occurrence of MPCs and 5 % fewer ice clouds than region 2D. In summary, these first results show that the distribution of low-level ice clouds and liquid-containing clouds is characterized by strong regional contrasts partly influenced by the latitude driven air temperature and the type of surface (ocean, sea ice, continental relief).

3.2 Seasonal variability of low-level cloud occurrences

In this section, we investigate the seasonal variations of low-level cloudiness for seven contrasting subregions of the Arctic and the results are presented in Fig. 3. Figure 3b shows that, in most regions, the annual cycle of total low-level cloud occurrence follows a bimodal distribution. The first peak occurs in late spring, when low-level clouds are present 50 % of the time in the Arctic (Fig. 3b, dashed black line). Previous studies have highlighted that the first cloud maximum is related to changes in the regional atmospheric circulation resulting from the weakening of the tropospheric polar vortex at the end of winter (Kay and Gettelman, 2009; Morrison et al., 2018). The second peak has a larger amplitude, reaching 60 % in autumn. However, Figure 3b also shows that the magnitude and timing of this double seasonal peak of high cloudiness exhibit regional variability. Most of the regions north of 70°N (2D, 2E, and 2F) are characterized by well-marked peaks with above average low-level cloud occurrences in May and in September or October. This feature is particularly striking in the eastern Arctic region (2F), where low-level cloud occurrence reaches almost 60 % in May and 75 % in October. Over the Bering Sea (1F), the spring and autumn local maxima are also clearly defined but more likely occur in April and November. This pronounced seasonal variation is less evident in regions influenced by the Atlantic Ocean (1A and 2A). Typically, higher and steadier occurrences are observed throughout the year (from 60 to 70 % in region 1A). The second peak of cloud occurrence observed in the autumn can be attributed to changes in surface conditions. In the northern regions (2E and 2F), sea ice retreat peaks in September. The open

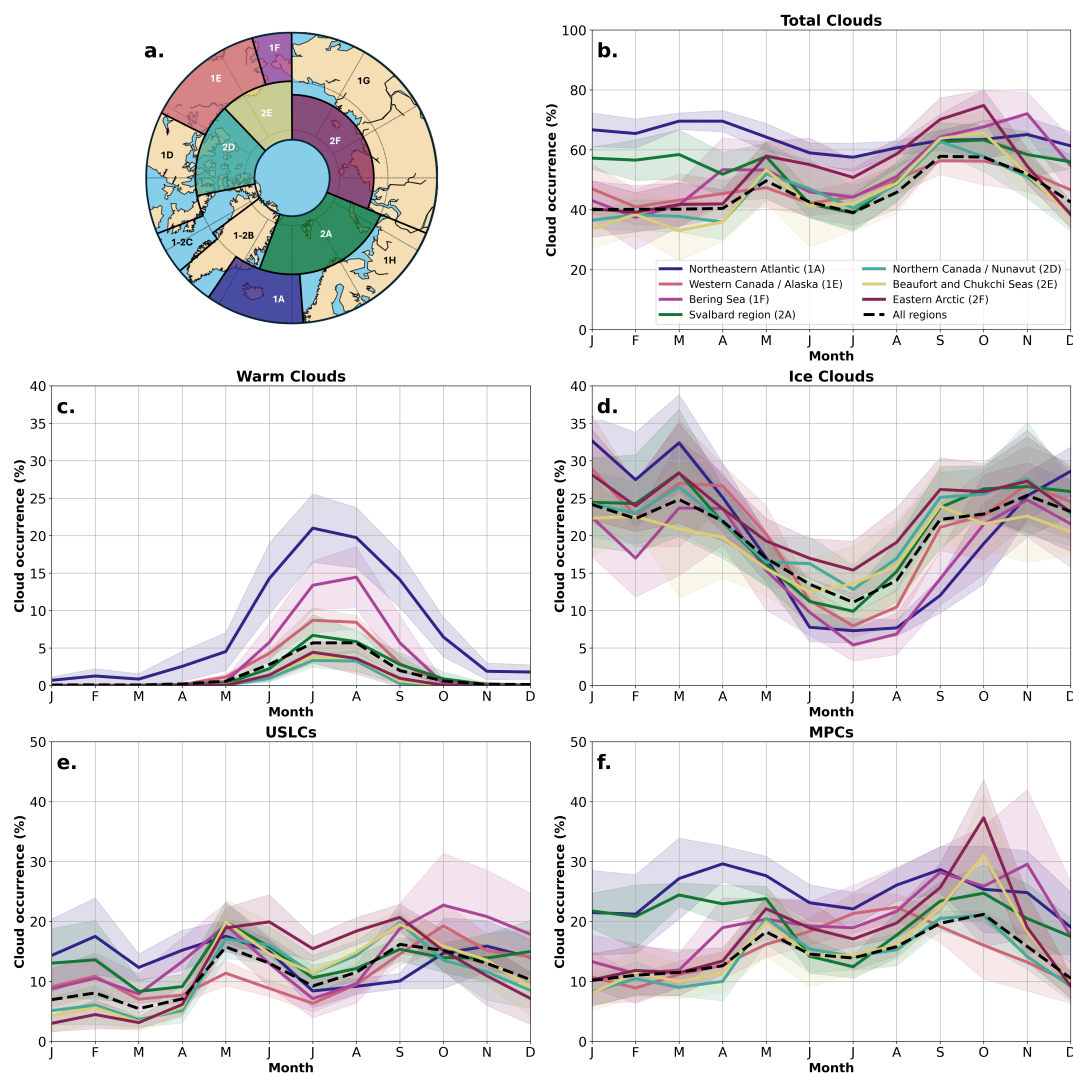


Figure 3. Monthly occurrence variations for different types of low-level clouds between 2007 and 2016: **(b)** total clouds, **(c)** warm clouds, **(d)** ice clouds, **(e)** USLCs, and **(f)** MPCs. Regionalization **(a)** with colored regions for monthly analysis. The colored areas around the curves represent the interquartile range. Zone 1 represents the low-latitude regions from 60°N to 70°N, excluding the Russian continental region. The letters for the different regions start from the North Atlantic zone (1A) and run from west to east. Zone 2 is the second high-latitude ring, from 70°N to 82°N. Regions in this latitude band are referred to in the same way as the first ring.

ocean facilitates the vertical transfer of moisture to the atmosphere, which fosters the development of low-level clouds until the return of the ice pack (Stroeve et al., 2012; Morrison et al., 2019; Yu et al., 2019).

315 The seasonal distribution of warm liquid and ice clouds does not follow the bimodal pattern observed for total low-level clouds. As expected, the occurrence of low-level warm clouds is characterized by a monomodal distribution with a maximum



observed in summer (Figure 3c). The Pan Arctic median OC_{warm} reaches 6 % in July and August. These clouds are mainly observed in low-latitude Arctic regions (1A, 1E and 1F), where a maximum frequency of occurrence of 20 % is recorded over the Northeast Atlantic region (1A) in July. Region 1A is also the only sector to experience warm cloud cover from mid-
 320 autumn to late spring characterized by OC_{warm} greater than 0 %. The monthly variations of low-level ice clouds are opposite to those of warm clouds. The occurrence of ice clouds is at its maximum in all regions from mid-autumn to late winter (Fig. 3d). During this period, OC_{ice} ranges from 20 % to 30 %. In the southern Arctic (1A, 1E and 1F), the amount of ice clouds decreases considerably in spring, reaching minimum occurrence values below 10 % in summer. However, this decrease is less steep over the northern seas of the western (2D and 2E) and eastern (2F) Arctic, where the persistence of low-level ice
 325 clouds is favoured by the colder atmospheric conditions. In these regions, OC_{ice} is typically greater than 15 % even during the summer months. These results indicate that the monthly variations of warm clouds and ice clouds are mainly driven by the meridional transport of heat and moisture. Although the distribution of these seasonal clouds is a consequence of latitude-driven temperature gradients, regional specificities persist. For example, ice clouds are observed more frequently in region 2F than in nearby oceanic regions (2A and 2E) throughout the year.

330 At the scale of the Arctic, the temporal evolution of the frequency of occurrence of USLCs (OC_{USLCs}) and MPCs (OC_{MPCs}) is similar to that of total clouds. Figures 3e and 3f show a seasonal bimodal distribution, featuring a first mode peaking at 15 % in late spring and a second one reaching 15 % in September for USLCs and 20 % in October for MPCs. However, significant differences are observed when these seasonal patterns are investigated at a regional scale. In autumn, when the second peak occurs, OC_{MPCs} reaches 35 % over the seas north of Siberia (1F). Differences in OC_{MPCs} of almost 20 % are also observed
 335 in spring between the Northeastern Atlantic region (1A) and region 1E. Moreover, regions 2F and 2E shift from being amongst the least covered by MPCs in summer (less than 20 % and 15 %, respectively) to becoming the regions with the highest MPCs occurrence in mid-fall (OC_{MPCs} is 25 to 35 %). In these regions, the opposite trend is observed for USLCs, with relatively high and steady values of OC_{USLCs} observed in summer, followed by a sharp decrease in autumn. Regions influenced by the transport of heat and moisture from the Atlantic Ocean (1A and 2A) exhibit the highest occurrences of MPCs during winter and
 340 spring (up to 30 % in region 1A). In contrast, the western and eastern Arctic regions (1E, 1F, 2D, 2E and 2F) have lower than average MPCs occurrence values (10-15 %). These regional differences also stand for USLCs but they remain less pronounced. Interestingly, the significant reduction of OC_{USLCs} observed at the beginning of spring (March) in the marine regions 1A, 2A, and 1F as well as the continental region 1E is balanced by an increase in ice clouds and a more moderate one in MPCs. From a broader perspective, the regional variations in the seasonal occurrence of these liquid-containing clouds cannot be explained
 345 solely by latitudinal temperature gradients and surface conditions. The frequency of occurrence of these clouds appears to be controlled by several environmental factors. Furthermore, our results show that USLCs and MPCs have a contrasted seasonal distribution at a regional scale, supporting the relevance of studying these clouds separately.

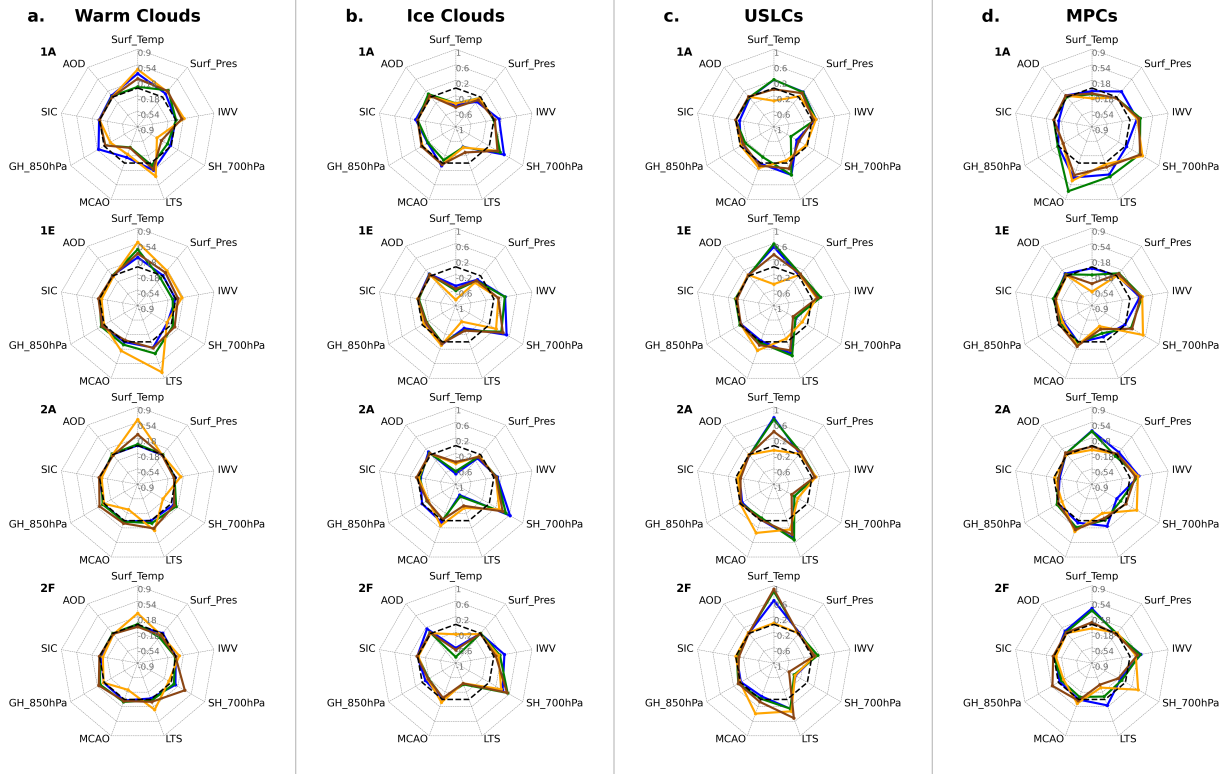


Figure 4. Normalized coefficients of MLR for low-level (a) warm clouds, (b) ice clouds, (c) USLCs, and (d) MPCs for 4 regions (1A, 1E, 2A, and 2F) during 4 seasons: (blue) winter, (green) spring, (orange) summer, and (brown) autumn. The dashed black line corresponds to the value zero.

3.3 Linking cloud-type occurrence to environmental conditions

3.3.1 Regional environmental conditions

350 In this section, we investigate the influence of environmental conditions on the regional and seasonal occurrence of low-level warm liquid clouds, ice clouds, USLCs and MPCs. Multiple linear regression (MLR) analyses are implemented to study the impact of the selected set of parameters (Section 2) on the distribution of cloud-type occurrences. Figure 4 shows the normalized MLR coefficients for the four types of low-level clouds in four Arctic regions (1A, 1E, 2A, and 2F) for the four seasons. These four regions were selected on the basis of their distinct seasonal variability, surface conditions (oceanic, continental, and sea ice), and geographical location as described in section 3.2. The MLR analysis shows that three parameters explain most of the variability in cloud occurrences. Surface temperature is anti-correlated with OC_{ice} and positively correlated with OC_{warm} and OC_{USLCs} (except during summer for USLCs). The impact of LTS generally follows the same trend as surface

355



temperature, highlighting more stable conditions associated with larger liquid cloud occurrences. The specific humidity at 700 hPa is positively correlated with OC_{ice} and negatively correlated with OC_{warm} and OC_{USLCs} .

360 Figure 4a confirms that the higher occurrence of warm liquid clouds is mainly associated with warmer surface temperatures and more stable conditions (high LTS probably associated with stronger inversions). The correlations are stronger in summer, especially in lower-latitude regions (regions 1A and 1E). In the North Atlantic region, the results of the MLR also show that negative SH_{700hPa} coefficients (i.e., anticorrelation) are associated with positive LTS and IWV coefficients in summer and to a lesser extent in autumn. This indicates that the maintenance of warm liquid clouds is also facilitated by the supply of heat
 365 and moisture from the lowest layers of the atmosphere, as previously shown by Morrison et al. (2019) and Taylor and Monroe (2023). Anticorrelations between OC_{warm} and the MCAO index (negative MCAO values) are also observed during summer in all selected marine regions. This confirms that warm air intrusions also contribute to the persistence of low-level warm clouds. This is particularly true in the Northeastern Atlantic sector (1A), where these southerly warm and moisture intrusions seem to play a role in each season, as previously reported by Woods and Caballero (2016).

370 Low-level ice clouds are more frequently observed in cold, humid, and less stable atmospheric conditions, regardless of the season (Fig. 4b). The MLR analysis shows that, apart from temperature and LTS, the presence of ice clouds is also conditioned by high specific humidity at 700 hPa. The presence of moisture at higher altitudes promotes the formation and growth of crystals in the upper cloud layers. In all regions, anticorrelations between OC_{ice} and geopotential heights at 850 hPa (GH_{850hPa}) suggest that ice clouds are observed more frequently in low-pressure systems, particularly in spring. During winter and spring,
 375 larger aerosol loading (AOD) seems to lead to higher OC_{ice} . The impact of polluted air masses on the presence of ice clouds is more clearly visible in the sea ice-covered region 2F (Koike et al., 2019; Coopman and Tan, 2023). It is also interesting to note that variations in sea ice concentration (SIC) do not appear to play a significant role in the occurrence of ice clouds, except in the Svalbard region (2A) during autumn.

The variability of the USLCs cloud cover is mainly influenced by changes in temperature, humidity, and stability conditions. However, Figure 4c shows that the trends are opposite to those of ice clouds. From autumn to late spring, more stable
 380 atmospheric conditions associated with higher temperatures and humidity confined to the lower layers favour the persistence of unglaciated supercooled liquid clouds. These relationships are particularly strong in regions 2F and 2A, and differ significantly from those established for ice and warm clouds. Our results also suggest that summertime USLCs occur more frequently when the regions are exposed to cold air mass intrusions (positive MCAO and lower air temperature), which contrasts with the pattern
 385 observed for warm clouds.

Interpreting MLR results for MPCs is more challenging, the seasonal and regional patterns differ substantially. This could be a consequence of the lack of representativeness of linear regression models or of the occurrence of MPCs being influenced by a larger number of seasonal environmental parameters. Nevertheless, Figure 4d shows that the presence of MPCs over marine regions (1A and 2A) is linked to increased cold air outbreaks and moisture intrusions (especially in spring and summer). Higher
 390 OC_{MPCs} in the continental region 1E are associated with more instability in the lower tropospheric layers, more moisture, and colder conditions. A similar pattern is observed in region 2F, but only in summer and autumn. The variability in sea ice



concentration does not appear to be a determining factor in explaining the frequency of occurrence of MPCs. However, in region 2A, our results suggest that these clouds tend to be more frequent when SIC decreases.

3.3.2 Key environmental factors controlling the cloud-type distribution

395 We will now investigate the variability of the dominant environmental parameters presented in the previous section, driving low-level cloudiness at both the regional and intra-regional scales. Regressions are performed for each grid point (2° latitude by 2° longitude), season and cloud-type, and only the most influential MLR coefficient with $R^2 > 0.2$ is selected, in line with previous studies of Naud et al. (2023) and Scott et al. (2020). Figure 5 confirms that on an annual basis, surface temperature, MCAO, LTS, geopotential height, and specific humidity are the main drivers of variability in low-level cloud occurrences.

400 However, intra-regional differences emerge when the most influential parameters are examined at a more local scale.

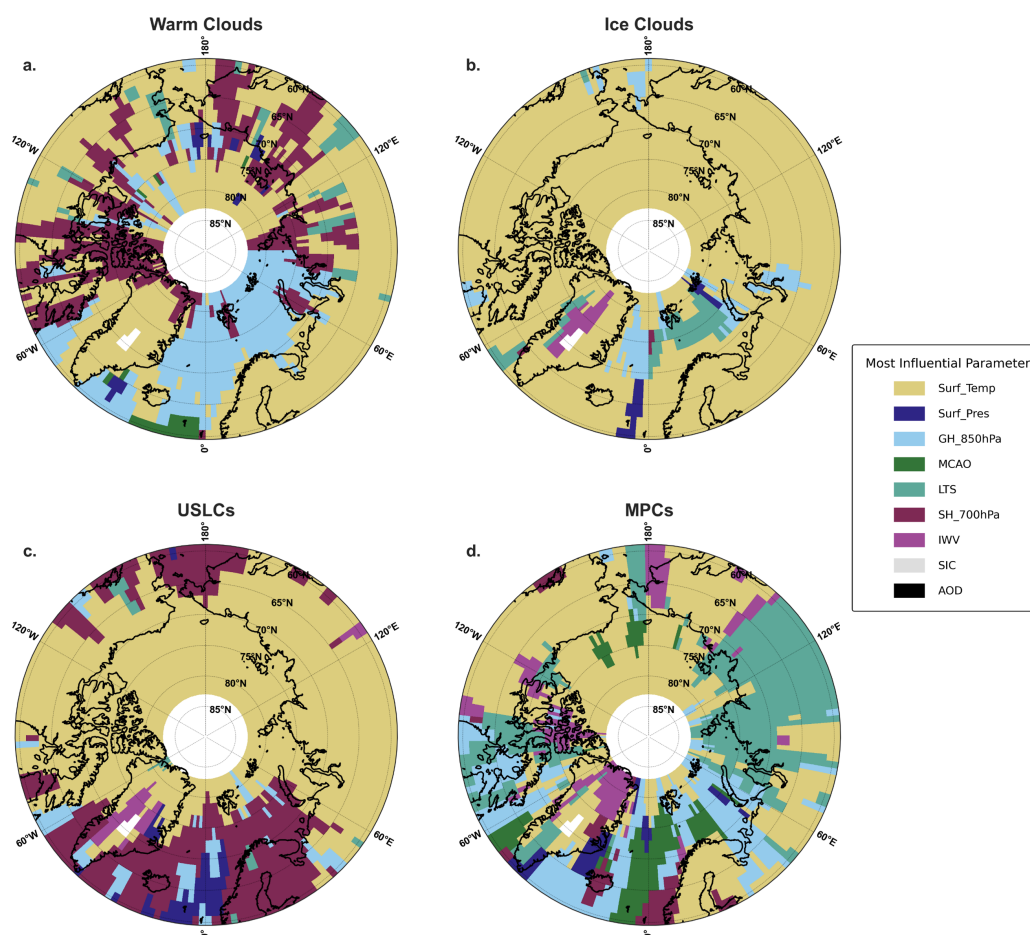


Figure 5. Most influential parameters of MLR for low-level (a) warm clouds, (b) ice clouds, (c) USLCs, and (d) MPCs for all seasons. The most influential parameter is represented if the MLR has an $R^2 > 0.2$.



Figure 5a shows the regions where GH_850hPa is the dominant factor controlling the frequency of occurrence of low-level warm clouds. In regions influenced by the North Atlantic Ocean, the advection of warm air masses results in higher geopotential heights, which promote the formation and maintenance of liquid clouds. Elsewhere, the distribution of OC_{warm} is mainly driven by the surface air temperature, except in some continental areas where SH_700hPa and LTS dominate the warm cloud patterns. However, one should bear in mind that the interpretation of MLR analyses is more meaningful in low-latitude regions for this type of cloud due to the number of data points.

In most of the eastern and western Arctic regions (Canada or Russia), surface air temperature is the dominant factor controlling the occurrence of low-level ice clouds (negative correlation, Fig. 5b) and USLCs (positive correlation, Fig. 5c). However, in particular in lower latitude regions with a marine influence (Bering Sea, Atlantic Ocean and seas in the vicinity of Greenland, Svalbard and part of Alaska), specific humidity at 700 hPa is the primary factor explaining the regional distribution of USLCs (negative correlation). Above continental regions, humidity aloft tends to promote the occurrence of winter-time ice clouds (Fig. S6 in Supplement). Over the Arctic seas, geopotential height at 850 hPa and LTS (negative correlations) are also important quantities that control the ice-cloud variability during the warmer summer and autumn seasons: colder air masses coupled with lower stability (more vertical mixing) contribute to the maintenance of ice clouds. Our analysis also indicates that surface pressure is the dominant factor in determining the persistence of USLCs and ice clouds within a narrow band to the east of Iceland. This region corresponds to the main storm track, which is associated with thicker and more numerous ice clouds (Zhang et al., 2023). The annual maps also highlight Greenland's singularity, where the amount of integrated water vapour is the most important factor in determining the occurrence and the phase partitioning of low-level clouds.

Figure 5d shows that the dominant factor controlling the distribution of MPCs occurrence varies significantly across regions. On an annual average, marine regions where the fraction of MPCs is high (1A, 2A, Beaufort and Chukchi seas) are mostly influenced by MCAO. The impact of cold-air outbreaks on MPCs is stronger during the transitional seasons (spring and autumn), whereas the advection of warm air and moisture above the oceans sustains the liquid phase of warm clouds in summer and of USLCs in Spring (Fig. S5 in Supplement). In central Russia and eastern Canada, LTS is the dominant MPCs controlling factor (positive correlation), whereas surface temperature is the most influential parameter in eastern and western arctic regions (mainly over the continents). Smaller pockets where IWV dominates are observed in northernmost continental regions (north of Greenland, Canadian islands). Higher occurrence of MPCs is also associated with lower GH_850hPa in oceanic regions located between 60°E and 60°W.

More generally, our results highlight significant regional contrasts in the distribution of cloud phases, primarily linked to the large-scale advection of heat and moisture and, at a finer scale, to the vertical transport of these quantities from the surface. In southern latitude marine regions, air mass intrusions (MCAO), the entrainment of dry/moist air aloft (SH_700hPa) and the heat and humidity fluxes from the open sea to the lower troposphere mainly drive the distribution of the phase partitioning of low-level cold clouds (MPCs, ice clouds, and USLCs). In most continental regions, increased instability (LTS) combined with colder and moister conditions aloft tends to favor the development of the ice phase. These first-order interpretations show that it is necessary to study in greater detail the links between the regional cloud characteristics and the surface conditions. The surface properties directly influence the stability of the lower atmospheric layers, the strength of the temperature and moisture



inversions (Brooks et al., 2017), which in turn impact the efficiency of turbulent fluxes and vertical mixing with the cloud layers. In the absence of reliable data on vertical velocities and surface fluxes, a statistical analysis of the fraction of clouds coupled to the surface across different seasons and regions can provide insight into these turbulent-driven processes.

3.3.3 Cloud–surface coupling

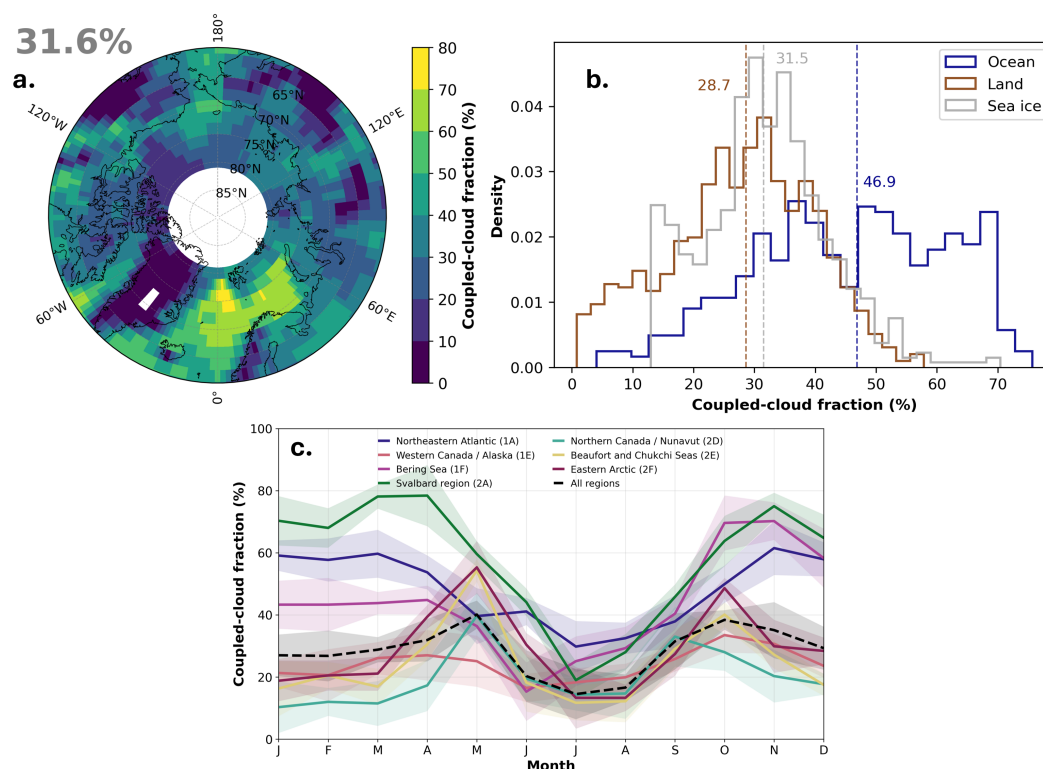


Figure 6. (a) Stereographic projection of median coupled low-level cloud fractions for the period 2007–2016. The number in the upper left indicates the median fraction for the entire study area. (b) Distribution of coupled low-level cloud fractions over different surface types (ocean, land, sea ice). Vertical dashed lines indicate the median values for each surface type (numbers on top of the lines). (c) Monthly evolution of coupled low-level cloud fractions over 2007–2016. Shaded areas around the curves represent the interquartile range.

440 A cloud is coupled with the underlying surface when its formation or evolution is directly affected by the thermodynamic properties of the surface layer. Surface-coupled clouds are typically boundary-layer clouds that are driven by heat and moisture fluxes from the surface to the cloud layers. A cloud can be considered to be coupled to the surface if the difference between the potential temperature at the cloud base and that at the surface is less than 0.5 K (Gierens et al., 2020). Otherwise, the cloud is decoupled from the surface, meaning that the turbulence inside the cloud is not directly related to the surface fluxes.

445 Figure 6a shows a stereographic map of the average annual spatial distribution of coupled clouds, expressed as a proportion of the total number of low-level clouds (fraction). On average, nearly 32 % of low-level clouds in the Arctic are coupled with



the surface. A higher proportion of coupled clouds are observed in oceanic regions (1A, 2A, and 1F), such as the Greenland, Norwegian and Barentz Seas surrounding Svalbard, where the annual average fraction exceeds 60 %. These values contrast with those obtained in the continental regions of Greenland, western Canada, central and eastern Russia, where fractions of less than 15 % are usually found.

Figure 6b provides a more quantitative view of the contrasts between the different types of surface. The probability density functions of the fractions of coupled clouds over open water, land, and sea ice clearly show that coupled clouds are more frequent over open ocean and seas. A median value of nearly 47 % is reached in these marine regions, while significantly lower values of 29 % and 32 % are obtained above land and sea ice, respectively. The shape of the distributions of coupled clouds over sea ice is similar to that over land but more positively skewed. The fraction of coupled-clouds above sea ice varies from 15 % to 70 %, while over land it ranges from 0 % to 58 %. The widespread distribution relative to the open ocean indicates that the proportion of coupled clouds can vary considerably from 5 % to over 75 %, depending on the typical seasonal and regional meteorological conditions. Figure 6c shows the climatology of the coupled cloud fractions over the different regions (defined in Fig. 3a) and confirms that clouds are more frequently coupled to the surface in maritime regions influenced by the North Atlantic (1A and 2A) and Pacific oceans (1F). From mid-autumn to mid-spring, the fraction of coupled clouds falls within the range of 40 % to 80 %. A pronounced autumn peak is observed in the Bering Sea and Svalbard regions, indicating that more than 70 % of the low-level clouds are coupled to the surface. A less substantial but still noticeable maximum also appears in most of the northern seas (2E and 2F, peaking at 40 to 50% in October) and some continental regions (1E and 2D, with autumn maxima close to 30 %). Another local maximum ranging from 25 % to 50 % can be observed in April or May in all regions except marine regions (1A, 1F and 2A). It is likely to result from increases in air temperature and instability of the lower troposphere, conditions that are favoured by the frequent occurrence of southerly or marine cyclonic flows in spring. In winter, minimum fractions of coupled clouds are observed in mostly continental and sea ice regions (less than 20 %), where stable and cold boundary layer conditions over land and sea ice tend to inhibit vertical mixing. In marine regions (1A, 2A and 1F), the fraction of coupled clouds remains above 40 % during winter, reaching values of up to 70 % across the seas surrounding the Svalbard archipelago. Our results also indicate that low-level clouds are mainly decoupled from the surface in summer in all regions (coupled fraction ranging from 30 % in 1A down to 15 % in 2E).

However, these results are only representative of low-level clouds as a whole, regardless of their thermodynamic phase. Figure 7 depicts the seasonal evolution of the coupled cloud fractions of the four different cloud types over open ocean, land, and sea-ice surfaces. Significant seasonal differences emerge between warm clouds and ice clouds that were not captured when the surface coupling was investigated at a regional scale. The results show that the majority of warm clouds are decoupled from the surface. The highest fraction of coupled clouds is found in summer on continents (20 % in July) and open seas (15 % in July and August; Fig. 7a). The pattern for low-level ice clouds is the opposite (Fig. 7b). From October to April, maximum values of 50–60 % are observed for the fraction of coupled clouds above open seas. During this period, the average cloud top height is close to 2300 m, which is more than twice that observed for low-level warm clouds coupled to the open ocean (Fig. S7a in Supplement). In summer, a minimum proportion of coupled ice clouds is observed (15 % in July), when these clouds are typically found at higher altitudes. A similar seasonal pattern is observed for ice clouds located over land and sea ice. However,



the fraction of coupled clouds is lower than above open water, with values ranging from 25 to 40 % from autumn to spring. Interestingly, our results also show that the average cloud top height of ice clouds coupled with sea ice surfaces is close to 2500 m, which is higher than over land or open sea (Fig. S7b).

485 The seasonal distribution of the coupled cloud fraction is similar for USLCs and MPCs when averaged over all surfaces (black curve in Figures 7c and d). However, the USLCs seasonal cycle is more pronounced. It features a sharp first peak in May, reaching 40 %, and a second peak in October, close to 30 % for all surface. Larger differences arise when seasonal variations are examined in relation to surface type. From September to May, approximately 42 % of USLCs are coupled to the surface above open water. A marked minimum of 16 % is observed during the summer. For MPCs, values range from 30
490 % from October to May to 18 % in summer (blue curve, in Fig. 7d). The fraction of USLCs coupled with the surface is much lower above sea ice (<20 %), except at the end of spring when it reaches 48 % in May (Fig. 7c). During this period, coupled USLCs are mainly packed close to the surface, with mean cloud top heights close to 1000 m (Fig. S7c). While the maximum in late spring maximum is also visible for MPCs above sea ice, a much stronger peak occurs in autumn. We find that 51 % of the MPCs are coupled to the sea ice surface in October. This sharp increase in the fraction of coupled clouds is a unique feature
495 of MPCs, which also corresponds to the maximum occurrence of MPCs observed over sea ice regions (Fig. 3f). Finally, our results also show that MPCs are less coupled to the surface above land than above open seas, except at the end of winter, when the fraction is approximately 30%.

Overall, our results indicate that the highest fraction of coupled cold clouds is usually above open water when strong temperature gradients occur between the surface and the lower troposphere (winter, spring and autumn). However, the seasonal
500 cycle of coupled clouds varies significantly with the cloud type (ice, mixed, and supercooled liquid) and the surface conditions. Surface turbulent fluxes seem to play a critical role in the phase partitioning of low-level clouds. In the following section, we will discuss how these surface processes, in combination with larger-scale thermodynamic conditions, affect the occurrence of MPCs and USLCs.

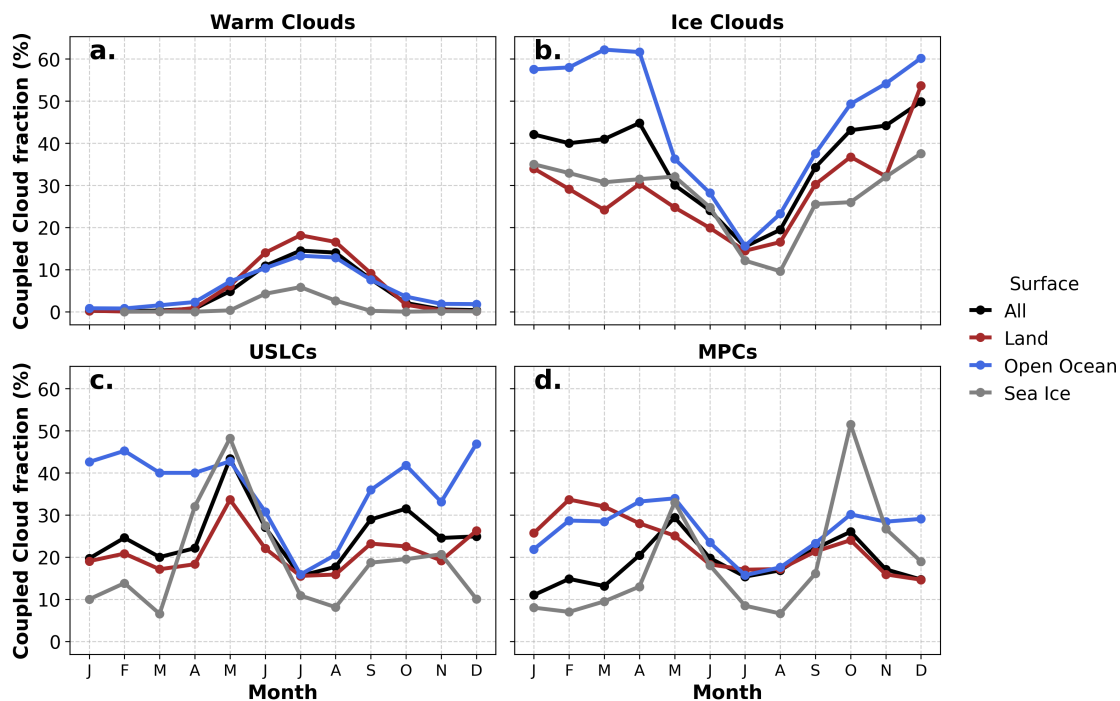


Figure 7. Monthly evolution of coupled cloud fractions over different surface types (ocean, land, sea ice, and all surfaces). Panels show (a) warm clouds, (b) ice clouds, (c) USLCs, and (d) MPCs.

4 Summary and Discussion

505 This study investigates the spatial and seasonal variability of low-level Arctic clouds (500–3000 m) using eight years of DARDAR-MASK v2.23 products from CALIPSO and CloudSat observations, processed with the DARDAR-SOCP algorithm. Our results highlight the widespread presence of low-level clouds across the Arctic, with a median occurrence of 51 %. This value is consistently higher than previous estimates based on AVHRR passive remote sensing measurements, which yielded average values ranging from 35 % to 57 % (Philipp et al., 2020). However, this median occurrence remains comparable to

510 the 45–50 % range obtained from 14 years of CALIPSO-GOCCP lidar observations reported in Jiang et al. (2024). Previous results on the occurrence of pan-Arctic low-level clouds are scarce despite their importance for the surface energy budget. Most studies have instead focused on the analysis of the occurrence of Arctic clouds throughout the tropospheric column. Mioche et al. (2015) and Cesana et al. (2024) used four years of DARDAR-MASK products (with different versions and resolutions) to show that tropospheric clouds were detected on average more than 70 % and 77 % of the time, respectively. Matus and

515 L'Ecuyer (2017) analyzed four years of 2B-CLDCLASS-LIDAR cloud phase classification products to obtain an annual cloud occurrence of nearly 75%. Across the entire tropospheric column, we obtain an eight-year average cloud occurrence close to



70 %, which is consistent with these previous estimates. It is also in accordance with the range of cloud cover values (60 to 80 %) inferred from ground-based remote sensing observations over western Arctic continental regions and Svalbard (Shupe et al., 2011). These comparisons with previous active remote sensing observations and products corroborate our results obtained with DARDAR-MASK v2.23 processed with the DARDAR-SOCP algorithm on a larger dataset.

Our analyses confirm that low-level clouds exhibit strong geographical and seasonal contrasts. As previously reported by Mioche et al. (2015) and Jiang et al. (2024), regions influenced by the North Atlantic Ocean are the cloudiest areas in the Arctic year round. In the Northeast Atlantic sector and across the seas near the Svalbard archipelago, we find annual low-level cloud occurrences of 67 % and 74 %, respectively. Low-level clouds are less frequent above continental areas of the western and eastern Arctic and over northernmost marine regions (Beaufort and Chukchi seas, Siberian seas), especially during winter ($OC_{all-ll} \approx 40$ %). Some of these differences can be explained by large-scale transport of heat and moisture during warm air intrusions (WAI), which are more frequent and intense in the Atlantic sector, even during winter (Woods and Caballero, 2016; Johansson et al., 2017; Nygård et al., 2019). While WAI can be associated with an increase in cloudiness, cold air outbreaks (CAO) and thermal contrasts between the surface and the lower troposphere can also affect the geographical and seasonal distribution of low-level clouds (Fletcher et al., 2016; Gierens et al., 2020). Over open oceans, stronger surface turbulent fluxes facilitate vertical transfer of heat and moisture, which promote low-level cloud formation, coupling, and persistence (Wendisch et al., 2023b). Our results indicate that, on an annual average, 32 % of the low-level clouds are coupled to the surface. This value is consistent with 23 % reported during the ASCOS campaign (Sotiropoulou et al., 2014). Moreover, we show that the proportion of coupled clouds is higher over open water (Atlantic and Pacific sectors) than across continental and sea ice regions. In particular, from the end of autumn to mid-spring, the fraction of coupled clouds exceeds 70 % in the seas around Svalbard, which is slightly higher than the 60 % reported by Griesche et al. (2021). In most regions of the western and eastern Arctic, low-level cloud occurrence follows a clear bimodal seasonal cycle, with maxima in spring and autumn. The first seasonal peak can be attributed to changes in weather conditions (e.g., cyclonic flows, warm air advections, etc.) that occur at the end of winter (Yu et al., 2019). The high cloud cover observed in autumn is probably a consequence of the changing surface conditions (Taylor and Monroe, 2023; Cesana et al., 2024). During this season, the maximum breakup of the pack ice facilitates the supply of moisture from the surface, which is favored by less stable conditions. Our results indicate that this seasonal pattern is more pronounced in northern regions of the eastern Arctic and over the Bering Sea, where sea ice retreats more slowly than in other regions and affects the timing of this second seasonal peak (Yu et al., 2019). The study by Jiang et al. (2024) also suggested a similar regional specificity for low-level cloud cover in autumn. During this period, our results show a strong increase in the proportion of coupled clouds in these regions, further supporting this hypothesis.

The most innovative aspect of our study is the analysis of the cloud-phase regional and seasonal variability. The DARDAR-SOCP algorithm based on the radar-lidar synergy categorizes low-level clouds as warm liquid, ice-only, mixed-phase (MPCs), or unglaciated supercooled liquid clouds (USLCs). Consistent with previous studies, our results show that warm and ice clouds have opposite seasonal cycles. The occurrence of warm clouds peaks in summer, with a maximum value of 20 % observed in the Northeastern Atlantic. These clouds are mostly decoupled from the surface (stable layer aloft) and are promoted by advection of warm air, although they evolve toward greater coupling with the surface during summer (in line with Brooks et al., 2017 and



Morrison et al., 2012). From mid-autumn to early spring, low-level ice clouds prevail over other cloud types across all regions. They are typically observed 25 % of the time during this period. Our results show that ice clouds tend to persist in cold, humid, and relatively unstable atmospheric conditions, which are often associated with low-pressure systems (in line with Liu et al., 2017). Accordingly, we show that over half of the clouds observed above open seas are coupled to the surface during the cold seasons. Above continental and sea-ice regions, low-level ice clouds frequently occur at higher altitudes and are more likely to be decoupled from the surface. Our results suggest that the ice phase can be sustained by moisture entrained from the humid layers above the cloud top.

Only a few studies have estimated the regional and seasonal occurrence of low-level MPCs, and to our knowledge, no studies have targeted Arctic USLCs specifically. We show that on average, MPCs and USLCs occur 17 % and 12 % of the time, respectively, throughout the Arctic region. Together, these cold liquid-containing clouds account for nearly 60 % of low-level clouds. This finding aligns with the results of Cesana et al. (2012), obtained from four years of CALIOP lidar observations. However, our findings show a higher median occurrence of low-level MPCs than the earlier Cloudsat-Calipso-based estimates of Matus and L'Ecuyer (2017) (i.e., 15 % throughout the entire tropospheric column). Unlike this study, we do not limit MPCs to single mixed-phase layers. Instead, we also include combinations of several successive liquid, mixed, and/or ice layers in our definition of MPCs. We believe that this representation more accurately reflects in situ observations, showing that low-level MPCs frequently consist of stratiform layers of supercooled droplets near the cloud top, as well as mixed-phase and ice layers below (McFarquhar et al., 2007; Mioche et al., 2017).

Our results confirm that the occurrence of liquid-containing clouds (MPCs and USLCs) follows a bimodal distribution, with maxima observed during the transitional seasons of spring and autumn, as suggested by Jiang et al. (2024). MPCs occur more frequently above marine regions, especially those influenced by the Gulf Stream (1A, 1C and 2A) or the Pacific Ocean (1F). This is also the case for USLCs, though the contrast with neighboring continental regions (1D and 1H, for instance) is less pronounced. Across the Svalbard region, our results on MPCs occurrence and seasonal variability are consistent with previous estimates based on CALIPSO-Cloudsat observations (Mioche et al., 2015) and ground-based measurements at Ny-Alesund station (Nomokonova et al., 2019). In these maritime regions, multi-linear regression analyzes show that the occurrence of MPCs is mainly correlated with the MCAO index, especially in spring and autumn. During these seasons, a higher proportion of coupled MPCs are observed above the open ocean (30 %). This suggests that changes in the thermodynamic structure of the lowest atmospheric layers during cold air outbreaks lead to intense surface turbulent fluxes that promote instability, coupling and persistence of MPCs. This is consistent with previous studies showing that CAO and WAI are expected to control cloud properties (Murray-Watson et al., 2023; Narizhnaya and Chernokulsky, 2024) and are predominant for MPCs (Woods and Caballero, 2016; Michaelis et al., 2022). Interestingly, USLCs occur more frequently when the lower atmosphere is more stable, surface pressures are higher, and geopotential heights at 850 hPa are lower. The most striking feature, however, is the systematic anti-correlation between OC_{USLCs} and specific humidity at 700 hPa. This suggests that entrainment of dry air and aerosol particles from above the cloud top could facilitate the maintenance of USLCs and delay the nucleation of ice crystals. Our results also show that, above open water, USLCs have lower heights and are more frequently coupled to the surface than MPCs, especially in winter and spring. This could be a consequence of large-scale subsidence events, which would



lead to stronger temperature inversions and more efficient mixing in the shallower marine boundary layer (Myers and Norris, 2013). Young et al. (2018) further investigated the impact of large-scale subsidence on the development of convection and the microphysical properties of marine stratiform, liquid-containing clouds. Their simulations showed that large-scale subsidence tends to reduce the entrainment of air from above into the cloud while increasing the cloud's liquid water path, the cloud-top radiative cooling and downdrafts. The resulting vertical mixing (and coupling) would help sustain the liquid phase and prevent rapid glaciation of the cloud.

In continental and sea ice regions, surface air temperature, LTS and the amount of water vapour (IWV) are the main parameters controlling the presence of MPCs. These parameters also influence the distribution of USLCs, albeit differently. USLCs tend to prevail in the lowest atmospheric layers under warmer and more stable conditions with drier air aloft. From late spring to summer, they appear more frequently than MPCs over certain marginal sea ice regions (2E and 2F) when surface coupling seems more pronounced. During this period, our results would indicate that, in the absence of moisture inversions, USLCs tend to be promoted more efficiently than MPCs during intrusions of colder air masses over relatively warmer surfaces. Once again, the presence of moisture at the cloud top seems to be a critical parameter in determining the partitioning between MPCs and USLCs. Generally, low-level mixed-phase clouds occur less frequently across these regions than above open ocean, except in autumn when the retreat of the sea ice is at its maximum. Our analysis shows that the MPCs frequency of occurrence can exceed 30 % in the western and eastern seas north of 70°N (2E and 2F). In autumn, the proportion of coupled clouds reaches a maximum value of 50 % due to more efficient heat and moisture transfer from the surface. During the SHEBA campaign, which took place in the Beaufort Sea, Shupe et al. (2006) also observed higher occurrences of MPCs, with cloud base near the surface, in September.

Our MLR analysis does not identify SIC as a primary factor controlling the occurrence of MPCs or low-level clouds in general. This result seems to contradict previous findings of Kay et al. (2016) and Cesana et al. (2024). It also indicates that parameters such as air temperature, LTS, humidity, and MCAO are more strongly correlated with cloud-type occurrences than sea ice extent or breakup. These thermodynamic drivers are, of course, linked to the surface conditions and the cloud coupling. However, we argue that the relationship between sea ice concentration and cloud-type occurrence depends heavily on the spatial scale and methodology employed. If we apply simple linear regressions restricted to grid cells with varying sea ice fractions, our results show clearer anti-correlations between SIC and liquid-containing clouds, including MPCs. SIC also appears to be positively correlated with ice clouds. Spearman's rank correlation coefficients are highest in autumn (Fig. S8 in Supplement), which is consistent with the findings of the study of Cesana et al. (2024). However, the overall correlations between SIC and cloud types remain weaker and more variable than those observed for most of the other thermodynamic parameters.

5 Conclusions

This study uses eight years of CALIPSO-CloudSat observations processed with a refined cloud-type classification program (DARDAR-SOCP) to provide a detailed characterization of the seasonal and regional distribution of four types of low-level Arctic clouds. The results confirm the ubiquity of tropospheric clouds in the Arctic, with low-level clouds (500–3000 m)



620 occurring 51 % of the time. Almost one-third of these clouds are coupled to the surface, a proportion that rises to nearly 50 %
 above open seas. From 60°N to 82°N, the median annual occurrence frequency of warm liquid clouds with temperatures above
 0 °C is 2 %. Ice clouds, which consist exclusively of ice crystals, occur 20 % of the time. Mixed-phase clouds (MPCs) are
 observed 17 % of the time, while the median occurrence of unglaciated supercooled liquid clouds (USCLs) reaches nearly 12
 625 in other studies. However, leveraging the synergy between radar and lidar allows us to differentiate USLCs from MPCs. It is
 important to segregate these two types of clouds because they are expected to experience different microphysical processes and
 lifetimes, and can impact the surface radiative budget and the hydrological cycle in different ways. To our knowledge, this is
 the first study to assess the distribution of USLCs across the Arctic.

Our results show significant regional and seasonal disparities in the distribution of these four types of low-level clouds. Their
 630 occurrence is primarily driven by variability in lower tropospheric air temperature, stability, humidity, air mass intrusions, and
 underlying surface conditions. The main findings of our study are as follows:

- Warm liquid clouds occur mainly in summer above the Northeastern Atlantic, where a maximum value of 20 % is
 observed. During this season, less than 20 % of these clouds are coupled to the surface. More stable and warmer lower
 tropospheric conditions associated with colder and dry air aloft facilitate the maintenance of these summertime clouds.
 635 The advection of warm air and moisture above the oceans also contributes to their persistence.
- From mid-autumn to early spring, low-level ice clouds prevail over other cloud types. In the mountainous regions of
 Alaska, central Siberia, and Greenland, they occur more than 30 % of the time, favored by orographic lifting. The
 regional distribution of these clouds is mainly controlled by the surface air temperature, the lower tropospheric stability
 and the specific humidity at 700 hPa. In northern continental and sea ice regions, ice clouds are primarily observed under
 640 cold, humid, and unstable conditions within low-pressure systems. Moisture inversions or intrusions from above the
 cloud top also seem necessary to maintain the ice phase. However, an additional source of humidity can be gained from
 warmer open seas, as we show that more than half of these clouds are coupled to the surface in marine regions during
 the cold seasons.
- Mixed-phase clouds are frequently observed in marine regions influenced by the Atlantic and Pacific oceans. The north-
 eastern Atlantic region and the seas surrounding the Svalbard archipelago are hotspots for MPCs, with median annual
 occurrences ranging from 25 % to 40 %. In these regions, cold air outbreaks over the warmer seas promote low-level
 instability, coupling with the surface and the vertical transfer of heat and moisture, ensuring the persistence of the mixed
 phase. The presence of humidity aloft also facilitates the maintenance of MPCs. Above most continental and sea ice re-
 gions, MPCs are characterized by a clear bimodal seasonal distribution. MPCs often occur at the end of spring and even
 650 more frequently in autumn, when they are observed more than 25 % of the time above the western and eastern Arctic
 seas. The regional distribution of MPCs seems to be influenced by wide range of thermodynamical factors. However, in
 these regions, the increase of MPCs and their coupled fraction appears to be correlated with the increase of the lower
 tropospheric instability and vertical mixing, promoted by the retreat of the sea ice in autumn.



– The regional and seasonal distribution patterns of low-level USLCs are similar to those of MPCs and mostly opposite to those of ice clouds. The highest USLCs occurrences (almost 20% annually) are found in the Greenland, Barents and Bering seas. From late spring to mid-autumn, the northern marine regions of the western and eastern Arctic experience a higher-than-average occurrence of USLCs, with maximum values of 20% reached in May and September. Marine USLCs are generally more coupled to the surface than MPCs in winter and spring, and have typically lower cloud top heights than MPCs and ice clouds. In all of these regions, we show that stable conditions, higher surface air temperatures and pressures, and low humidities at higher altitudes seem to favor the longevity of USCLs over ice-containing clouds. Our results suggest that the entrainment of dry air and aerosol particles from aloft could be an important process that affects the phase partitioning of low-level clouds.

The results of this study are valuable because they offer a new, quantitative assessment of the occurrence of different types of low-level clouds over eight years in various regions of the Arctic. The study also examines the statistical relationships between the distribution of cloud types and large-scale environmental conditions. Although similar studies have been conducted previously, they have rarely or never focused specifically on the regional differences between low-level MPCs, USLCs, and ice and warm liquid clouds. The detailed statistics and environmental dependencies identified in this study can serve as valuable references for comparisons with large-scale model outputs and for improving cloud-phase parameterizations. In order to draw more comprehensive conclusions about the environmental conditions and processes that drive the distribution of low-level clouds, it would be necessary to study the influence of additional dynamic and thermodynamic variables. In particular, the impact of wind patterns, air mass transformations, and large-scale subsidence on low-level MPCs and USLCs should be investigated more comprehensively. The transport of aerosols and their ability to act as cloud condensation nuclei and ice nuclei remains an important aspect to explore. Non linear approaches could also bring new insights on how these parameters drive the regional and seasonal distribution of the cloud phase.

Our results have highlighted the strong influence of the open ocean in sustaining the maintenance and surface coupling of cold clouds. Further dedicated analyses at smaller scale are required to understand the role of surface turbulent fluxes, shallow convection, and the entrainment of moisture from above the cloud top, on the cloud phase distribution. In a future work, we plan to investigate the impact of turbulence, temperature and moisture inversions on the microphysical properties of low-level mixed phase clouds using airborne in situ measurements in the Svalbard region.

Finally, although DARDAR-SOCP cloud-type classification suffers from several shortcomings close to the ground, the database established in this study can be used for more reliable microphysical retrievals. In this context, recent advances in lidar–radar synergistic methods designed to retrieve the properties of ice, supercooled water, and mixed-phase clouds (VarPy-Mix, Aubry et al., 2024) can benefit from our results to establish climatologies of cloud microphysical properties throughout the Arctic. It would also be interesting to extend our methodology to recent EarthCARE lidar and radar observations (Illingworth et al., 2015), to ensure consistent monitoring of low-level cloud types and identify potential occurrence trends in a changing Arctic environment.



Data availability. “DARDAR-MASK.v2.23” and “01kmCLay.v4.20” products used for cloud phase retrieval and aerosol data in this study are available at <https://www.icare.univ-lille.fr/> with free registered access. Sea ice concentration data from the AMSR-E/AMSR2 satellite instruments are available at <https://seaice.uni-bremen.de/sea-ice-concentration/amsre-amsr2/>.

690 *Author contributions.* AD: Writing of the original manuscript, data processing, dataset analysis. GM: Edited the manuscript and analyzed the results. QC: Edited the manuscript and analyzed the results. CB: Methodology and data processing. JD: Methodology and manuscript editing. OJ: Edited the manuscript, analyzed the results, and supervised the project.

Competing interests. The authors declare that have no conflict of interest.

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