Cloud cover and cloud types in the Eurasian Arctic in 1936–2012

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Abstract

The Arctic is a cloudy place. It has been recognized that the Arctic cloud cover is sensitive to different climatic factors such as sea ice extent and atmospheric circulation indices. Moreover, several influential climate feedbacks, for example, the summertime cloud-radiation feedback, have been recognized. Yet, the cloud cover studies were limited in time to the satellite era observations and fragmentary data sets from meteorological stations. Here, we present the complete long-term cloud records from 86 meteorological stations in the Eurasian Arctic. The stations are located on the coast and islands of the region from the Barents to Chukchi Seas. Thus, this study is complementing and extending the study by Chernokulsky et al. (2017) where the cloud data from the Norwegian through Kara Seas were presented. Our data set comprises the entire period of observations at each station. However, we present the area-wide analysis only over the historical period of 1936–2012 when there were sufficient density of stations and cloud records for the coherent analysis. The total cloud cover, which on multiannual average constitutes 69–74% in different areas, increases in the warmer periods. The strongest increase is found in the convective cloud cover, particularly in the Chukchi Sea. We observe statistical evidence of transition between stratiform and convective cloud types. The cloud characteristics reveal the strongest correlations with the Atlantic circulation indices and the sea ice concentration in all Eurasian Arctic areas. The correlations with the Pacific circulation indices are much less significant. The obtained cloud data sets disclose much smaller scale features and variability, which deserve further research.

KEYWORDS

Arctic clouds, climatic indices, cloud cover, cloud types, early 20th century warming, sea ice, stratocumulus transition, surface observations

1 | INTRODUCTION

Arctic climate is changing more rapidly than anywhere else on Earth (IPCC, 2013; Meier et al., 2014). Large areas in both the Atlantic and Pacific Arctic are now exposed to more intensive air-sea interactions over prolonged periods with ice-free water. These surface changes are increasingly influencing the lower atmosphere and cloud characteristics. Already Curry et al. (1996) showed that the ice-free water surface boosts vertical heat and moisture fluxes. The enhanced air-sea exchange transforms both the cloud cover and the cloud types. Satellite and surface observations and
model simulations suggested an intrinsic link between the Arctic climate change, the sea ice concentration (SIC), and the cloud cover (CC) characteristics (see, e.g., Wang et al., 2012; Jun et al., 2016).

The Arctic clouds have a significant impact on the regional energy budget, thus, playing an important role in the Arctic climate system (Shupe and Intrieri, 2004; Cesana et al., 2012; Kay and L’Ecuyer, 2013), modifying the magnitude of the Arctic warming and the regional climate response (Kay et al., 2016; Goosse et al., 2018). The net cloud radiative forcing in the Arctic is positive. It can reach about 20 W/m² in winter (Shupe and Intrieri, 2004). Surface air temperature under an overcast sky in the central Arctic is 6–9 K higher than under a clear sky (Walsh and Chapman, 1998). Thus, increasing cloudiness may induce a strong positive feedback that would further rise the surface temperature (Graversen et al., 2014; Cox et al., 2015).

Climate and numerical weather prediction models simulate the Arctic CC imperfectly, with non-negligible biases (e.g., Chernokulsky and Mokhov, 2012; Jiang et al., 2012; Zygmuntowska et al., 2012; Karlsson and Svensson, 2013; English et al., 2015; Liu and Key, 2016). Even the CMIP (Climate Model Intercomparison Project) model ensemble overestimates the CC, and hence, the cloud-radiative feedback (Kretzschmar et al., 2018). The Arctic climate projections, while robustly capturing many of the cloud-related feedbacks in the Arctic (e.g., Zelinka et al., 2012), are not coherent when the low-level clouds are compared (Vihma et al., 2016). The models may significantly benefit from inter-comparisons between the observed CC and the corresponding quantities from historical model runs.

The published studies of cloud climatology, cloud physics and impact are still based upon the short and scattered observational records. Satellite-born sensors provide information only since the end of 1970s (e.g., Schweiger, 2004; Wang et al., 2012). A longer period can be evaluated given the data from the routine meteorological observations. A comprehensive analysis of such data was conducted by Eastman and Warren (2010a, 2010b); however, their data sets are available since 1971 (the land-based observations) and 1954 (the ship-based observations). An early analysis by Przybylak (1999) included the CC data sets from 19 Arctic stations covering 1951–1990. More recently, Khlebnikova et al. (2014) analysed the data sets from 150 Russian stations covering 1951–1990. Relatively long but geographically scattered data sets are available from the Russian North Pole drifting stations since 1955 (Makhtas et al., 1999; Schweiger, 2004). The longest observational Arctic cloud climatology was published in (Chernokulsky et al., 2017). This publication will be referred to hereafter as C17. The published climatology covers the period since the end of 19th century; however, it is limited to the Norwegian, Barents and Kara Seas and to the analysis of the total cloud cover only. Consequently, there are still a major knowledge gap in detailed historical climatology of the CC and the cloud types in the Eurasian Arctic (EA).

Observations of the morphological cloud types provide a considerable added value to the cloud classification, which is usually limited to the distinction of the clouds by their elevation above the ground. The cloud types have distinct radiative, albedo and mixing properties (Minnett, 1999). They bear an imprint the cloud forming processes and their historical occurrence (Eastman and Warren, 2010b). For instance, more frequent observations of stratocumulus (Sc) versus stratus (St) clouds point out on the more intensive air-sea interaction (coupling) and the increasing role of the local surface sources of air moisture. A transformation from stratiform to convective clouds leads to a subsequent reduction of the area-averaged downward thermal radiation and enhancement of the absorbed short-wave solar radiation. More aggregated convective clouds reduce the CC at all levels and might increase the outgoing longwave and reflected shortwave radiation fluxes (Tobin et al., 2012). A lack of long-term cloud type climatology constitutes a significant gap in understanding of the cloud-radiative effect and the cloud–sea ice interaction changes under the historical climate variations in the Arctic.

This study aims to present a consistent covering the longest available period of observations. This dataset includes visual observations from meteorological stations in the Eurasian Arctic (from the Barents to Chukchi Seas) over the entire period of historical observations. The records extend over two relatively warm periods and one cold period. This is in the strong contrast to the satellite cloud records, which cover only the recent warm period when unprecedented sea ice loss has been observed. This study essentially extends the C17 analysis. In addition to the total CC, we present a comprehensive low-level cloud type analysis. Furthermore, we calculated correlations between the cloud characteristics and essential climate factors and indices. Although we analyse only a very limited subset of hypothesis linking cloudiness with some climate factors and feedbacks, we expect that the presented cloud statistics and datasets would be useful for wider communities of climate modellers and experts.

The manuscript is structured in a traditional way. Section 2 presents a detailed description of the dataset and the processing methodology. Section 3 presents the results. Here, Sections 3.1 and 3.2 provide an assessment of the climatology and variability of cloud cover and cloud types, while Section 3.3 extends the study with the analysis of cloud characteristic relationships with climate change indicators. Section 4 delivers a discussion, and Section 5 summarizes the results and draws the conclusions.
2 | DATA SETS

Initial observational data were made available to us by the All-Russian Research Institute of Hydrometeorological Information (RIHMI) (Bulygina et al., 2014; Chernokulsky et al., 2017). The routine meteorological observations have been collected at 89 Russian meteorological stations in EA (Figure 1). Three geographical areas with distinct cloud climatology were specified. A West Eurasian Arctic (WEA) includes the meteorological stations along the southern coast of the Barents and Kara Seas where sea ice is absent or appears only briefly in wintertime. A Central Eurasian Arctic (CEA) includes the stations to the north of the Taymyr peninsula, on the Laptev Sea coast and on the central Arctic islands (Svalbard, Franz-Josef Land, Novaya Zemlya, Severnaya Zemlya, and the New Siberian Islands). An Eastern Eurasian Arctic (EEA) includes the stations on the East Siberian and Chukchi Sea coast and Wrangel Island.

Each report in the RIHMI dataset contains information on the total and low CC as well as on the morphological cloud types. These characteristics are determined during visual sky inspections by station observers. The total, \( n_{\text{tot}} \), and low, \( n_{\text{low}} \), CCs were determined as a fraction of the full sky, which is covered with all types of clouds and with low-level cloud types, respectively. In addition, trained meteorological observers determined presence of 10 standard morphological cloud types following the World Meteorological Organization (WMO) guidelines that includes high-level clouds (cirrus, cirrostratus, and cirrocumulus), middle-level clouds (altostratus, altocumulus and nimbostratus [Ns]), and low-level clouds (cumulus (Cu), cumulonimbus (Cb), stratus (St), and Stratocumulus (Sc)). The RIHMI cloud data slightly differ from the WMO standard code recommended by the World Weather Watch Global Observing System (WMO, 2015). These differences are as follows: \( n_{\text{tot}} \) and \( n_{\text{low}} \) both are given in tenths (1/10 units) instead of octas (1/8 units); nimbostratus clouds are treated as the low-level clouds rather than the middle-level clouds; special codes for cloud breaks and cloud traces are used (see C17), but information on the amount of each cloud type is absent (Chernokulsky et al., 2011).

The RIHMI cloud data were processed as follows. All data on \( n_{\text{tot}} \) and \( n_{\text{low}} \) were converted from tenths to octas for consistency with C17 and other studies (e.g., Eastman and Warren, 2010a, 2010b). The cloud breaks and traces were counted as 7 and 0 octas, respectively. All reports were checked for meeting a moonlight criterion (Hahn et al., 1995) that filters out a priori uncertain observations conducted in lightless conditions. This criterion disqualified about 25% of all the reports. As much as 70% of the reports did not meet the criterion during the polar night at some northernmost stations. Figure 2 shows the historical changes in the number of the reporting stations and the total number of the cloud reports with and without the moonlight criterion applied. Furthermore, all qualified reports were averaged with equal weights for each month. In this way, we obtained the monthly mean values of \( n_{\text{tot}} \) and \( n_{\text{low}} \). We excluded the monthly mean data if less than 10 days with the qualified reports were found in that month. Each day must have at least one qualified report—recall that clouds were observed four- or eight-times per day (Figure 2). We also calculated frequency of the cloudless, \( f_{\text{clr}} \), and overcast, \( f_{\text{ovc}} \), conditions. The frequency of the cloudless conditions is defined as \( f_{\text{clr}} = N_{\text{na} = 1}/N_{\text{na}} \), where \( N_{\text{na}} \) is the total number of the qualified reports; and \( N_{\text{na} = 1} \) is the total number of the qualified reports with cloudiness no more than 1 octa. Similarly, the frequency of the overcast conditions is defined as \( f_{\text{ovc}} = N_{\text{na} > 1}/N_{\text{na}} \). More details on the \( n_{\text{tot}} \) processing as well as the description of the reasoning behind the applied assumptions could be found in C17.

Processing of the morphological cloud types was focused on the different low-level clouds, namely, on: the convective...
clouds (Cu and Cb), which specific CC is denoted as $n_{\text{CuCb}}$; the stratiform clouds (St and Ns) ($n_{\text{StNs}}$); and Sc ($n_{\text{Sc}}$). We point out that $n_{\text{low}}$ is not equal to the sum $n_{\text{CuCb}} + n_{\text{StNs}} + n_{\text{Sc}}$ because the different cloud types could be observed simultaneously. We split $n_{\text{low}}$ equally between the observed types for those reports which contain simultaneous observation of various low-level cloud types (e.g., St and Sc, or Cu and Sc). Moreover, some reports indicate $n_{\text{low}}$ but do not specify the cloud type. It is coded as “undetermined” because of haze, fog, blizzard, darkness etc. In this case, $n_{\text{low}} > n_{\text{CuCb}} + n_{\text{StNs}} + n_{\text{Sc}}$. Very early years of observations contain about 20–26% of such reports. This number declines to a few per cent at the end of 1950s. Apparently, the “undetermined” reports appeared due to a poor training of the observers in the early period. To eliminate the artificial trend in the cloud characteristics, we made a correction assuming the constant ratio of the cloud types in determined and undetermined reports for each year. For instance, the corrected (“real”) $n_{\text{Sc}}$ depends on the observed $n_{\text{Sc, O}}$, $n_{\text{CuCb, O}}$, and $n_{\text{StNs, O}}$ as follows: $n_{\text{Sc}} = n_{\text{low}} \cdot n_{\text{Sc, O}} / (n_{\text{CuCb, O}} + n_{\text{StNs, O}} + n_{\text{Sc, O}})$ [as an example, assume that observed CC of all three types in a particular month is 15%, and amount of $n_{\text{low}}$ is 50% (which means undetermined $n_{\text{low}}$ equals to 5%), in this case, $n_{\text{Sc}} = 50 \cdot \frac{15}{15 + 15 + 15} = 16.7\%$]. Eastman and Warren (Eastman and Warren, 2013) found artificial abrupt changes in the cloud type data for some Russian stations, which were also reflected in changes of precipitation types (Chernokulsky et al., 2019). Such discontinuities in the station records are absent in this analysis.

Although observations in the Russian Arctic started in 1893, this study considers for analysis only the data over 1936–2012. We processed the complete stations’ time series, but prior to 1936, the data have significantly lower quality and sparse geographical coverage (see C17 for more details). After 1936, systematic biases are below 3% (5% for $f_{\text{oce}}$) of the seasonal mean values of the respective cloud characteristics. The assessment was based upon the monthly mean variations for each station. The seasonal means were calculated if at least two monthly means were available for a season. We adopted here a shifted season convention, for example, the winter season includes January, February and March (JFM), the spring season includes April, May and June (AMJ), and so on. The study includes also the spatially aggregated analysis for selected areas (WEA, CEA, EEA). The aggregation procedure was adopted from C17. We selected 1981–1990 as a period for counting the mean values for each station, which were subsequently used for calculating

**FIGURE 2** The historical overview of the cloud data used in this study. The annual number of the reporting stations is shown with the red solid line; the total annual number of the cloud reports— with the black solid line; the number of the qualified cloud reports with the moonlight criterion applied—with the black dotted line; the amount of the low-level cloud reports with an undefined type—with the black dotted line. The blue text explains key changes in the observations. The horizontal colour lines indicate the periods that were analysed in the previous works, which used the station data in these areas. (Stanhill, 1995) (S95) study is shown as the purple line, which covers the period of 1964–1991; (Przybylak, 1999) (P99) study (light magenta line) covers the period of 1951–1990; (Eastman and Warren, 2010a) (EW10) study (green line)—1971–2007; (Chernokulsky et al., 2011) (ChBM11) study (red line)—1991–2010; (Khlebnikova et al., 2014) (KhMS14) study (orange line)—1951–2010; C17 study (blue line) covers the period of 1936–2013.
anomalies at each station for each year. The anomalies at all stations in operation in the given year were averaged within each area (averaging for 10° longitudinal sectors first). Further, the regional mean for the 1981–1990 period was added to the average anomaly of the given year providing the resulting values of the cloud characteristics. This procedure accounts for spatial heterogeneity of the stations and reduces an unintended systematic bias due to dropping (or including) systematically more (or less) cloudy stations.

3 | RESULTS

3.1 | Cloud climatology

The Arctic is a cloudy region. However, the CC significantly varies between the areas. The long-term averaged $n_{tot}$ is close to 74, 72, and 69% in the WEA, CEA and EEA, respectively (Table 1). The EEA is the least cloudy area. The convective $n_{CuCb}$ varies from 12% in the WEA to just 2% in the almost permanently ice-covered CEA. This difference emphasizes the role of open water in enhanced vertical mixing in the atmosphere. It signals transitions in the cloud structure and cloud-radiative feedbacks expected with sea ice retreat. The Sc cloud fields are rather common in all three regions, having the maximum $n_{Sc}$ of 37% in the CEA.

The low-level clouds dominate the sky over the open-water area, especially the sky above the seashore stations in the Barents Sea (WEA) and in the Chukchi Sea (EEA). The typical values of $n_{low}/n_{tot}$ are close to 0.7–0.8 in the WEA and 0.6–0.7 in the EEA. These values reach 0.8 at the Uelen station (the easternmost station). Satellite observations provide even larger $n_{low}/n_{tot}$ ranging from 0.80–0.85 in the WEA to 0.75 in the EEA (Liu et al., 2012a). The mid- and high-level clouds are significant in the CEA where $n_{low}/n_{tot}$ is around 0.6 over the historical period. The research literature associates the mid- and high-level clouds with frontal systems (Curry et al., 1996) and moisture transport from lower latitudes (Vavrus et al., 2011; Liu et al., 2018), the low-level clouds depend on local evaporation and to the large extent on sea ice conditions (Palm et al., 2010; Eastman and Warren, 2010b; Vavrus et al., 2011; Esau and Chernokulsky, 2015).

The Arctic clouds exhibit strong seasonal variations. The largest $n_{tot}$ of 80–90% are observed in autumn, while the smallest $n_{tot}$ of 50% are observed in spring (Figure 3). The specific cloud type amounts exhibit similar variations, albeit the stratiform clouds (St, Ns) do not show such a clear seasonal cycle in any area. The occurrence of the clear sky and overcast conditions also has the strong seasonal cycles. The strongest seasonal cycle is found in the Sc amount (Figure 3). It has the maximum in summer and autumn. This amount reaches 50–65% in September and drops to 10–20% in March in all areas. Cloud observations from ships and drifting stations (Eastman and Warren, 2010b) have showed an increased amplitude of the annual cycle of $n_{tot}$ in more northern areas. The seasonal cycle of $n_{Sc}$ dominates the seasonal cycle of $n_{tot}$. Thus, the cloud types are important for understanding of the Arctic processes.

The Arctic clouds are sensitive to the climate anomalies in the region. We specified three climatic periods. The early period (1936–1965) comprises relatively warm climate conditions. The intermediate period (1961–1990) was colder. It had the largest area of multiyear ice in the Arctic ocean. The recent period (1983–2012) demonstrates the amplified Arctic warming and unprecedented sea ice retreat, especially in the EEA. We also specify a period of contemporary changes (1997–2012) when both the surface air temperature and the sea ice loss exhibit strong positive trends.

Observed cloudiness reflects changes in the regional climate (Figure 4; Figures S1–S3 in Data S1). The CEA demonstrates increase in $n_{tot}$ whereas the WEA and EEA demonstrate significant increase in $n_{CuCb}$. This increase has been captured by the ship observations (Eastman and Warren, 2010b), while the satellite data display both positive (mostly in summer and spring) and negative (in winter and autumn) trends (Schweiger, 2004; Wang and Key, 2005; Eastman and Warren, 2010a).

Bi-modal dichotomy of the clear and overcast sky conditions characterizes cloudiness in the central Arctic (Walsh and Chapman, 1998; Makhtas et al., 1999). We found a high proportion of the cloudless and overcast sky only in the CEA (Figure S1 in Data S1). The annual mean sum of $f_{clr}$ and $f_{ovc}$ remain around 80%, partitioning by 20 and 60% in the first and second historical periods and by 10 and 70% in the third period. Both $f_{clr}$ and $f_{ovc}$ have the largest amplitude of their annual cycles (35–45%). In the WEA, the clear and overcast sky records were less common in the first period ($f_{clr}$ ~5–10%, $f_{ovc}$ ~40–50%), and even less common in the

| TABLE 1 | Annual mean (and its standard deviation) of different cloud characteristics (%) for the three regions over the entire 1936–2012 period |
|-----------------|-----------------|-----------------|---------------|---------------|---------------|-----------------|---------------|-----------------|---------------|
| $n_{tot}$ | $n_{low}$ | $f_{clr}$ | $f_{ovc}$ | $n_{CuCb}$ | $n_{Sc}$ | $n_{StNs}$ |
| WEA | 74.2 (2.4) | 52.1 (4.4) | 12.9 (2.0) | 44.7 (4.7) | 12.5 (2.3) | 33.3 (3.0) | 6.2 (3.0) |
| CEA | 71.7 (2.6) | 43.3 (6.3) | 17.4 (3.1) | 51.2 (5.9) | 1.8 (1.1) | 37.4 (4.0) | 4.1 (3.0) |
| EEA | 69.1 (2.2) | 39.2 (5.6) | 18.0 (3.7) | 45.0 (5.8) | 3.3 (1.6) | 31.2 (4.4) | 4.8 (2.9) |
second and third periods ($f_{\text{clr}} \sim 5\%$, $f_{\text{ovc}} \sim 20\%–40\%$, respectively). In the EEA, $f_{\text{clr}}$ decreased from 20 to 25% in the first period to 15–20% in the third period with the largest drop in February–April. The decrease of $f_{\text{ovc}}$ from 50–60% to 40–50% could be observed in the data, with the largest drop in July–October. Simultaneous reduction of $f_{\text{clr}}$ and $f_{\text{ovc}}$ has resulted in increasing frequency of the scattered and broken clouds.

### 3.2 Observed changes in cloudiness

The revealed multi-decadal cloud variations manifest fundamental climate shifts unfolding in the region. The changes are patchy, but majority of stations displayed lower $n_{\text{tot}}$ in 1970–1980 and higher $n_{\text{tot}}$ in 1940s and in 2000s (Figure 5; Figure S4 in Data S1). The absolute maxima of $n_{\text{tot}}$ and $f_{\text{ovc}}$ (Figure 5; Figure S6 in Data S1) were observed in the WEA in 1940s. In the CEA and EEA, the $n_{\text{tot}}$ maxima are observed in the 21st century. The historical variations of $f_{\text{ovc}}$ in the CEA and EEA were insignificant. By contrast, the variations of $f_{\text{clr}}$ (Figure S5 in Data S1) were substantial, especially in the CEA, where many stations showed lower $f_{\text{clr}}$ in 1930–1940 and in 2000s. The seasonal means of $f_{\text{clr}}$ substantially vary from one year to another, especially in the CEA, where the years with $f_{\text{clr}}$ of nearly 50% have been followed by the years with almost no clear sky conditions.

The low-level clouds play a significant role in the CC. The low-level CC, $n_{\text{low}}$, had a long-term negative trend reversing to a positive one in 1990s (Figure S7 in Data S1). The observed changes of $n_{\text{low}}$ result from a delicate balance of changes of different low-level cloud types (Figure S8–S10 in Data S1). This balance is sensitive to the atmospheric circulation (Esau and Chernokulsky, 2015; Liu et al., 2018) and the sea ice concentration (SIC). The historical changes of the convective cloud types could be connected to the SIC variability. The recent decades witness robust increase of the convective CC (Figure 6 and Figure S8 in Data S1). At the Kola Peninsula, $n_{\text{CuCb}}$ has slightly increased from 22–25% in 1940s to 25–28% in 2000s. The strongest increase is found in winter and spring. The CEA is only weakly touched by those changes. The stratiform CC had the maxima in 1940s for $n_{\text{Sc}}$ and 1950s for $n_{\text{StNs}}$; and the minima by the end of 1990s (Figure 6; Figures S9, S10 in Data S1).
A general decline of $n_{Sc}$ is found in the CEA. The decline in $n_{Sc}$ could be observed in November–April during the transition between the first and second periods as well as in May–October during the transition between the second and third periods. The long-term changes of $n_{Sc}$ constitute the main factor of the changes in $n_{low}$ (Figure S11 in Data S1). The annual mean $n_{SNC}$ changed in the WEA from 7 to 12% in 1936–1965 to 3–8% in 1961–1990 and then to 1–4% in 1983–2012. A similar pattern of changes (6–13% to 2–5% and then 1–4%) is observed in the EEA. These surface observations conclusively indicate the transformation of the cloud types expressed in the long-term decrease in the stratiform and increase in cumuliform cloud types, especially pronounced since late 1990s.

The revealed cloud changes in the historical perspective are coherent with the previously published, yet more limited studies. For example, Przybylak (1999) used a smaller subset of stations to obtain a positive $n_{tot}$ trend in the WEA and CEA over winter and spring of 1951–1990. We found the same tendency for $n_{tot}$ in the CEA and the EEA for the entire 1936–2012 period (Figure 6; Figure S4 in Data S1). (Stanhill, 1995) reported a decrease of surface solar irradiance at the Krenkel station (Franz-Josef Land) over 1964–1989, which has been related to the increasing cloudiness. At the same time, the decreasing CC...
in summer and autumn in the EEA has resulted in some increase of irradiance (Stanhill, 1995; Khlebnikova et al., 2014). The decreasing irradiance in 1986–2010 was associated with larger low-level CC since 1990s (Khlebnikova et al., 2014). These observations were widely discussed (Schweiger, 2004; Eastman and Warren, 2010b; Wang et al., 2012; Wu and Lee, 2012).

The discussion related the CC changes to the SIC (Palm et al., 2010; Eastman and Warren, 2010b; Abe et al., 2016; Li et al., 2017) through mechanisms of enhanced evaporation and vertical turbulent mixing (Boisvert et al., 2015).

It is useful to mention relevant studies, which were based upon the North Pole station data. Schweiger (2004) found that the increase of \( n_{\text{tot}} \) began in the central Arctic already in 1980s. Makshtas et al. (1999) reported decreasing \( f_{\text{cl}} \) and \( f_{\text{ovc}} \) in winter and summer over 1955–1991. The decreasing \( f_{\text{ovc}} \) was found in the WEA and EEA. The simultaneous decrease of \( f_{\text{cl}} \) and \( f_{\text{ovc}} \) is a result of the low-level cloud type changes; and more specifically, it follows the observed increase of convective and decrease of stratiform clouds (Khlebnikova and Sall, 2009; Chernokulsky et al., 2017).

### 3.3 Correlations with climate change indicators

The observed cloud variability likely reflects specific physical mechanisms, teleconnections and feedbacks acting in the
Arctic climate system. We obtained correlations between the CC and the selected circulation and climatic indices (IND). We will abbreviate these correlations as, for example, \((n_{\text{tot}}; \text{IND})\) in the text below. The following indices were used. The mean surface air temperature of the Northern Hemisphere (NH SAT) is used as an index of the global warming. The Atlantic circulation anomalies are represented through the Atlantic Meridional Circulation (AMO), North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices. The Pacific circulation anomalies are represented through the Pacific—North American (PNA) and Pacific Decadal Oscillation (PDO) indices. The ocean regional circulation anomalies in Barents Sea are related through the Kola section average temperature (Kola T). The large-scale regional moisture transport is described through the transport to the Barents—Kara Seas (MT BK) and to the Laptev—East Siberian—Chukchi Seas (MT LESC). The SIC changes in the same areas are connected through the SIC BK and SIC LESC indices. Additional details about these indices could be found in the Supporting Information in Data S1.

The Mann-Kendall correlation coefficients have been calculated for (CC; IND) pairs for detrended time series for four shifted seasons at each station with the observation record longer than 30 years (Figures 7–10; Figures S12–S14 in Data S1).

The strongest and the most coherent correlations are found in the WEA. The correlations with \(n_{\text{low}}\) are stronger in this region, whereas the correlations with \(n_{\text{CuCb}}\) are weaker but still significant at many stations. The winter (JFM) and autumn (OND) seasons show the strongest CC correlations with the large-scale circulation indices, such as \((n_{\text{tot}}; \text{NAO})\), \((n_{\text{tot}}; \text{AO})\) and \((n_{\text{tot}}; \text{MT BK})\). The winter correlations are higher for the western WEA stations, which are close to the open water area and experience more intensive storm activity. The autumn correlations are higher for the eastern WEA stations, which are close to the seasonally open water area. We cannot confirm either weaker correlations of the high-level CC with the SIC or weaker correlations of the low-level CC with the circulation and moisture transport indices.

The considered correlations in the CEA are generally weak and incoherent, but in the EEA, we again found stronger correlations. The strongest correlations are found for...
They point out on inherent connections between the SIC changes and the global warming amplification in this area. Since the correlations are stronger in autumn, the CC in the EEA is likely to be sensitive to local factors such as the SIC, as it is consistent with Taylor et al. (2015) findings. The strong connections with the Kola T and AMO indices in the EEA are, however, surprising. Similarly surprising, we found weak correlations with the Pacific indices (PNA, PDO) and the regional moisture transport (MT LESC).

The spring (AMJ) and summer (JAS) seasonal correlations were found to be the weakest and insignificant in Eurasian Arctic. It was expected as the atmosphere over still cold ice-covered seas is stably stratified and impeding the cloud formation. On this background, it is interesting to observe strong correlations between MT BK, Kola T and \( n_{tot} \) (much weaker with \( n_{low} \)). It tells that the moisture transport in spring and summer significantly influences the higher clouds in the WEA and the CEA.

## 4 | DISCUSSION

### 4.1 | Added value of the historical cloud records from the Eurasian stations

The Arctic clouds lack charisma of powerful convective clusters in lower latitudes or persistence and extent of subtropical fields of stratocumulus clouds. Nevertheless, the regional climatic impact of the Arctic clouds could be rather significant, especially when they are considered from the perspective of cloud-albedo-radiation feedbacks (Kay and Gettelman, 2009; Goosse et al., 2018). Understanding of this
impact is frequently compromised by gaps in cloud observations (Eastman and Warren, 2010b), by shortness of the records as well as by discrepancies in remote sensing data products (Chernokulsky and Mokhov, 2012; Wu and Lee, 2012). Climate models and reanalysis products also reproduce cloudiness with significant biases and errors (Chernokulsky and Mokhov, 2012; Jiang et al., 2012; English et al., 2015). To date, the most comprehensive observational Arctic cloud climatology was published in C17. The present study extended this observational climatology to the eastern part of the Eurasian Arctic.

We extended the cloud records to the important early climate change periods. The historical observations would help to re-assess the CC contribution in the Arctic climate change. In all regions, cloudiness had decreased over the historical period till mid-1980s, whereas the significant increase of cloudiness and its transition to the convective cloud types have not been observed before mid-1990s. This longer perspective indicates that earlier studies of the short-term trends in the satellite-derived clouds (Schweiger, 2004; Wang and Key, 2005; Boccolari and Parmiggiani, 2018) might under-estimate rates of the changes due to the noted transition from the negative to positive trends in the total CC. So far, studies of the early Arctic warming have either not reported the cloud changes at all (Wood and Overland, 2009; Yamanouchi, 2011) or, when the historical forcing climate simulations were run, reported rather controversial impact of clouds (Pithan and Mauritsen, 2014).

One may note that the previous studies were mostly concerned with interactions between the SIC, the NH SAT variability and the meridional circulation anomalies (Yamanouchi, 2011; Smersrud et al., 2013; Pithan and Mauritsen, 2014). Only a few studies recognized the role of clouds in the climatic feedbacks (Vavrus, 2004; Schweiger et al., 2008; Walsh et al., 2009; Leibowicz et al., 2012; Jun et al., 2016; Goosse et al., 2018). The large-scale circulation effects were best studied with reanalyses or climate simulations. However, the models themselves require calibration
against the observational data sets (Jiang et al., 2012; English et al., 2015). The model calibrations are presently limited to the short recent periods. The analysis runs over the period of satellite observations (Boccolari and Parmiggiani, 2018). This study closes the mentioned data gap by providing the longer dataset.

4.2 Climatic factors controlling cloudiness

The Arctic climate is controlled by the local and large-scale environmental factors. This convenient dichotomy is adopted to distinct between the processes in the atmospheric column and those of hemispheric horizontal advection. Hereafter, we omit quotation marks while bearing in mind that there cannot be unambiguous dichotomy as all processes are interacting. The local factors are related to the SIC, winds and lower atmospheric stability over sea ice and open water. They have the largest effect on the low-level and convective clouds. The mid- and high-level clouds are more sensitive to the large-scale circulation factors. Similar sensitivity is revealed by fields of convective and stratocumulus clouds. Our results (Figures 7–10) show tight correlations between the low-level CC and the local factors, especially in the EEA. In the WEA, the low-level CC has also revealed sensitivity to the large-scale circulation indices and moisture convergence. The central argument behind the SIC connections to the low-level clouds was that the larger area of relatively warm open water can drive stronger moisture flux convergence. The stratiform clouds in the lower atmosphere are also sensitive to the static stability of the respective layers. The correlations \(n_{\text{tot}}, \text{SIC BK}\), \(n_{\text{tot}}, \text{SIC LESC}\) are the strongest in autumn when cold air outbreaks are frequently observed. Our data reveal significant summer season correlations with \(n_{\text{CuCb}}\), whereas no significant correlations with \(n_{\text{tot}}\) are found.

The Arctic cloudiness was linked not only with the anthropogenic warming, increase of the meridional heat and moisture...
advection (Jakobson and Vihma, 2010; Sorokina and Esau, 2011; Dufour et al., 2016; Hao et al., 2019), but also with the sea ice loss and enhancing of the turbulent exchange over open water (Taylor et al., 2015; Liu and Schweiger, 2017). The strong links to the SIC have been documented in both satellite records, retrospective meteorological analysis and climate models (Kay and Gettelman, 2009; Palm et al., 2010; Jun et al., 2016). Liu et al. (Liu et al., 2012b) found that 1% decrease in the SIC corresponds to 0.36–0.47% increase in the CC. Abe et al. (Abe et al., 2016) pointed out that the cloud cover is increasing with a delay of about 1 month with respect to the seasonal sea ice retreat.

4.2.1 The local factor: a cloud—sea ice feedback

The satellite observations over 1982–2004 have shown that the Arctic has warmed up and become cloudier in spring and summer but cooled down and become less cloudy in winter (Wang et al., 2012). Correspondingly, annually averaged surface albedo has decreased. The net cloud radiative forcing in the Arctic is positive reaching about 20 W/m² in winter (Shupe and Intrieri, 2004). The surface temperature under the overcast conditions was found to be 6–9 K higher than that under the clear sky (Walsh and Chapman, 1998). The trend of the annual averaged cloud forcing at the surface was found to be about −2.1 W/m² per decade (Wang et al., 2012), thus, indicating a damping effect of cloudiness on the surface warming. Cox et al. (2015) reported a positive feedback between the surface temperature and the additional cloud forcing due to an infrared cloud radiative effect. This effect is estimated to add 1–5 W/m² to the cloud forcing. It may increase to 5–15 W/m² under the projected Arctic warming by 2050. The climate models overestimate the CC, and hence, the cloud-radiative feedback in the region (Kretzschmar et al., 2018). Kapsch et al. (2016) run a modelling study of clouds, humidity, and heat anomalies that all affect downwelling shortwave and longwave radiation.
budget in the Arctic. It was found that positive longwave radiation anomalies are associated with the cloudy and humid conditions. The most significant impact is revealed in spring and early summer, whereas the winter anomalies showed only a little effect. This brief review suggests that more clouds can induce a strong positive feedback, further raising the surface temperature and reducing the SIC even more (Graversen et al., 2014; Goosse et al., 2018).

4.2.2 | The large-scale factor: sensitivity to the Atlantic circulation anomalies

The large-scale factor relates cloudiness with the large-scale circulation anomalies, the meridional energy transport and the regional moisture convergence. Indirectly, through the regional circulation response on the sea ice loss and the latent heat release in clouds, this large-scale factor is also sensitive to changes in the Arctic cloudiness (Handorf et al., 2015). Here, however, we emphasize our attention to horizontal advection and teleconnections, that is, to the processes where the cause and response are not always collocated. The large-scale factor is more difficult to study using in situ observations than satellite data. The satellite products under-represent the low-level clouds when they are overlapped by the upper-level clouds. Contrary, the in situ records under-represent the upper-level clouds. The large-scale factors have more impact on the upper-level clouds as they could be insulated from the surface by the temperature inversion; and vice versa, the low-level clouds may be less sensitive to advection of clouds, moisture and heat, whereas their formation is controlled by the surface layer turbulence and the processes in the atmospheric column (Fan et al., 2015; Vihma et al., 2016).

The Arctic Ocean Experiment 2001, which has been conducted in the WEA, disclosed this decorrelations between the meteorological variability in the PBL and in the free atmosphere (Tjernström, 2005)—those two layers were separated by temperature inversion. The large-scale factor acts differently in the CEA and EEA where the SIC creates a permanently cold surface layer. The cold air over sea ice forces uplift and the subsequent latent heat release in advected moist air. This mechanism largely controls the mid- and high-level stratiform clouds as it has been demonstrated by Komatsu et al. (2018) in their modelling study. In the long run, the CC is determined by cyclonic activity. Dufour et al. (2016) study has quantified that 88–94% of the meridional moisture transports at 70°N is carried by the synoptic eddy activity.

One of the most hotly debated topics is related to the relative roles of the Atlantic and Pacific circulation anomalies in the Arctic variability and to the role of cloudiness in this chain of influence. The stronger correlations with the Atlantic indices are clearly identified for all cloud types, levels and seasons in our analysis. The correlations with the Pacific indices are much weaker. They become statistically significant only at some scattered stations in some seasons. Neither the CEA nor EEA stations demonstrate stronger connections to the Pacific (PNA, PDO) indices than to the Atlantic (AMO, NAO, AO) indices. The strongest anti-correlations with the PDO index are found in the WEA in spring and autumn. The larger influence of the Atlantic circulation anomalies is known from many statistical and modelling studies, which relate the NH SAT index with the SIC and the circulation patterns (Handorf et al., 2015; Tokinaga et al., 2017).

It is interesting to look at possible signatures of an Arctic dipole circulation pattern in the CC records. The Atlantic circulation anomalies excite a dipole pattern (identified through the sea level pressure anomalies) with the secondary and opposite-sign circulation centre in the EEA and the eastern parts of the CEA (Wu et al., 2006; Alexeev et al., 2017). Indeed, \( n_{\text{tot}} \) has positive correlations with the NAO and the AO in the Barents-Kara Seas but weakly negative correlations in the Laptev-East Siberian Seas. The strongest opposition in the correlations could be seen in \( n_{\text{tot}} \) in winter and in \( n_{\text{low}} \) in autumn.

4.3 | Transitions to the convective cloud types

The Arctic cloud cover mostly consists of the stratiform cloud types. However, its transition to the convective clouds is more and more frequently observed in the recent years. Considering the convective clouds (Cu, Cb), one may expect that they link the local and large-scale factors, the PBL and the free atmosphere motions. Arguably, an individual Cu cloud is controlled by the local factor such as the convective available potential energy and static stability of the PBL (Eastman and Wood, 2016). However, the convective clouds in the Arctic are almost exclusively observed as extended cloud fields linked to marine cold air outbreaks. In this sense, they are a synoptic-scale phenomenon and controlled by the large-scale circulation. The cloud fields of Cu and Cb are observed when a cold air mass protrudes over open water (Esau and Chernokulsky, 2015). Fletcher et al. (2016) found that the low-level clouds in the marine cold air outbreaks tend to have large \( n_{\text{low}} \) and low-to-moderate optical thickness. Their surface longwave radiative effect is significant, but they do not contribute substantially to the shortwave radiative effect. The outbreaks are ubiquitous in the WEA where cold air is advected over the relatively warm ice-free Barents Sea (Smedsrud et al., 2013). Here, the convective clouds are observed in 10–30% of the records. Since the last decade of the 20th century, Cu and Cb are increasingly observed in the EEA (Ding et al., 2017).
The Arctic stratocumuli (Sc) have been identified as an important component of the climate feedbacks in the region. Wood (2012) noted that $n_{Sc}$ peaking in late summer can considerably change the surface energy budget and the amount of heat in the upper ocean mixed layer. The clouds are found in the areas where the air-water temperature difference is small and insufficient to drive the cloud-forming convection. Stratocumuli are frequently the mixed-phase clouds. This physical property is particularly difficult to capture in the climate models. Sotiropoulou et al. (2014) found that the mixed-phase clouds were frequently decoupled from the surface as the radiative cooling at the cloud top produces turbulence, which generates a cloud-driven mixed layer. The stratocumulus fields also organize themselves into open and closed cloud cells. The cell type depends on whether the surface heating or cloud-top cooling dominates in the maintenance of the cloud convection. These clouds are sensitive to the state of the surface. They exhibit high correlations with the SIC and Kola T indices as well as with the NH SAT and AMO indices. The correlations are much stronger in autumn and winter (see Figure 10). Reconciling Sotiropoulou et al. (2014) and Taylor et al. (2015) results with our cloud statistics, we suggest that the Sc and Cu fields could undergo mutual transitions when the surface turbulent fluxes enhance (decay) and couple (decouple) the cloud layer from the surface sources of mixing and moisture. Lloyd et al. (2018) used field studies and satellite data to demonstrate that the Sc-Cu transition was also related to cold air outbreaks. Such transitions are likely to have place further downstream in the CEA and the EEA where the Atlantic storms are less frequent.

4.4 An example of the increasing Arctic convective cloudiness

A spectacular example of the recent Sc-Cu transition and increasing convection in the EEA is given by the observations at the Wrangel Island and Uelen stations. Increasing wildness of weather is becoming a symbol of the Arctic warming. More Atlantic storms penetrate into even higher northern latitudes bringing convective instability and moisture (Alexeev et al., 2011, 2017; Walsh et al., 2012; Hao et al., 2019). Enhanced frequency of the convective cloud types in the WEA and to some degree in the CEA are found in our study for the long period. Following the SIC reduction, the convective clouds have recently appeared in the EEA as well. This development has been observed also in the satellite data covering the Beaufort-Chukchi Seas (Wu and Lee, 2012; Liu and Schweiger, 2017). Figure 11 exemplifies the convective cloud field around the Wrangel Island station as well as the dramatic increase of $n_{CuCb}$ since about 2005. One can observe that the transition to convective cloud types opens significantly larger fraction of the surface to absorption of solar radiation. A triple positive feedback could be observed when (1) more short-wave solar radiation reaches (2) the darker open water surface, and when (3) the clouds and air moisture return more long-wave radiation back to the surface.

In the historical perspective, the EEA has been heavily covered by thick multi-year ice prior to the recent warming period. The convective clouds in the area were reported earlier, but they have been connected to the convection over sea ice polynyas (Ebner et al., 2011). The unprecedented increase of the convective cloud types in the recent
observations signals the sea ice anomalies at scales well beyond their historical range. The Wrangel Island and Uelen stations have not reported any convective clouds in winter and very few in autumn and spring in the 20th century. In summer, some amount of Cu and Cb (5–10%) was observed also during the colder period (1960–1970) because the cold air intrusions were observed there even in summer. By contrast, the return of the convective clouds in the 21st century was robustly linked to the sea ice loss and to accumulation of evaporated water in the lower atmosphere (Wu and Lee, 2012). We found surprisingly strong correlations ($n_{CuCb}$, SIC LESC) and even ($n_{CuCb}$, SIC BK) in the EEA. The region-wide correlations also reveal more significant correlations with the Kola T (JFM), PDO (AMJ), SIC BK (JFM) and SIC LESC (AMJ, JAS, OND).

5 | CONCLUSIONS

The historical climatology of the meteorological (visual) observations of the total and low cloud cover and of the cloud types is constructed. The entire Eurasian Arctic (89 meteorological stations) from the Barents Sea to the Chukchi Sea is included in this dataset and analysis. There are: 34 stations in the Western Eurasian Arctic (WEA) spanning over the southern coast of the Barents and Kara Seas; 38 stations in the Central Eurasian Arctic (CEA) spanning over the Arctic islands and the coast to the north of Taymyr and the Laptev Sea; and 17 stations in the Eastern Eurasian Arctic (EEA) spanning over the coast of the East Siberian and Chukchi Seas and the islands nearby. Here, we did not include the stations in the Norwegian Sea, which have been considered in C17. The complete dataset from this and C17 studies is available at the Nansen Center web page (https://www.nersc.no/project/gcloud).

In concordance with the fragmented and shorter previous studies, we found that the Arctic is a cloudy place. The total cloud cover demonstrates a distinct annual cycle with the minimum in February–March and the maximum in September–October. The total cloud cover was smaller during the cold period (1960–1980) with the large SIC. The low-level CC had the minimum in 1980–1990 in all areas and in all seasons. The stratocumuli clouds are the most frequently observed low-level clouds, and they have the most pronounced seasonal cycle. The significant transitions between different cloud types were observed in the historical perspective. The stratiform clouds prevailed in the early warm period (1930–1940) and decline since then. The convective clouds (Cu and Cb) have been increasing in the WEA during the whole considered period (1936–2012), whereas they become more common in the CEA and the EEA only since 1990s. The CC in all areas is significantly stronger correlated with the Atlantic than with the Pacific circulation indices and climatic factors, such as, for example, the SIC. Yet, the cloud cover varies substantially from one arctic area to another.

The WEA is the cloudiest area in the Arctic with the annually mean total CC of 74.2%, the low-level CC of 52.1%, and the convective CC of 12.5%. Here, the seasonal cycles of the total and stratiform cloud cover are the least pronounced; the interannual changes and the historical CC trends are also the smallest. Total cloud cover was the largest in WEA in 1930–1940s. Contrary, the convective CC shows the largest seasonal and interannual variations as well as the most pronounced long-term positive trend. The WEA clouds are the most sensitive to the large-scale circulation indices and the meridional moisture transport.

The CEA clouds demonstrate a distinct bimodal distribution of the clear sky and overcast conditions, which together constitute almost 70% of the observations. However, the long-term changes of the low-level cloud types have substantially reduced this bimodality. The seasonal cycles of the cloud characteristics, particularly those of Sc, are the most pronounced in the CEA. The Sc clouds determine the seasonal cloud cycle here. The amplitude of the seasonal cycle gradually diminishes in the recent decades. The CEA has become cloudier in the recent years.

The EEA has the smallest CC with the most significant role of the mid- and high-level clouds. The small low-level CC should be attributed to the reduced amount of the Sc clouds. It is remarkable that the convective CC in the EEA is rapidly increasing in the 21st century in all seasons on the background of the warming and the prominent SIC reduction. In general, the recently observed total CC in this area is the largest since 1930s. Moreover, our data suggest that the cloud cover undergo a significant transformation process forced by the enhanced air-sea exchange over seasonally open water. We observed for all areas, and in the EEA specifically, that the low-level stratus and stratocumulus types are being transformed to the convective cloud types.

Our analysis of cloud climatology can significantly add to the model development as well as to the fundamental understanding of the Arctic cloud processes and feedbacks. The Arctic cloud response and impact on the large-scale circulation factors in the climate perspective are still poorly understood. To progress in this direction, the climate models must be better calibrated on the historical cloud cover variations. Looking at the impact of the local factors, rather rudimentary understanding of the Sc-Cu cloud type transition exists to date. The Arctic convective clouds have not been studied from the perspective of the area-wide developing cloud fields. The coupling-decoupling processes in the low-level cloud layers are also neither physically nor geographically understood. Significantly more knowledge is required to relate the changes in the Arctic radiation (and generally, heat) balance with the Arctic cloud cover—cloud type climatology.
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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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