Strong Dependence of Wintertime Arctic Moisture and Cloud Distributions on Atmospheric Large-Scale Circulation

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ABSTRACT

This study gives a comprehensive picture of how atmospheric large-scale circulation is related to moisture transport and to distributions of moisture, clouds, and surface downward longwave radiation in the Arctic in winter. Anomaly distributions of the abovementioned variables are compared in 30 characteristic wintertime atmospheric circulation regimes, which are allocated from 15 years (2003–17) of mean sea level pressure data of ERA-Interim reanalysis applying the self-organizing map method. The characteristic circulation regimes are further related to known climate indices—the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), and Greenland blocking index—as well as to a frequent high pressure pattern across the Arctic Ocean from Siberia to North America, herein called the Arctic bridge. Effects of large-scale circulation on moisture, cloud, and longwave radiation are to a large extent occurring through the impact of horizontal moisture transport. Evaporation is typically not efficient enough to shape those distributions, and much of the moisture evaporated in the Arctic is transported southward. The positive phase of the NAO and AO increases moisture and clouds in northern Europe and the eastern North Atlantic Ocean, and a strong Greenland blocking typically increases those in the southwest of Greenland. When the Arctic bridge is lacking, the amount of moisture, clouds, and downward longwave radiation is anomalously high near the North Pole. Our results reveal a strong dependence of moisture, clouds, and longwave radiation on atmospheric pressure fields, which also appears to be important from a climate change perspective.

1. Introduction

Atmospheric moisture and clouds play a central role in radiative processes (Morrison et al. 2012) and the hydrological cycle (Vihma et al. 2016) in the Arctic. Through radiation, clouds and atmospheric moisture regulate the surface energy balance and surface

temperature. For most of the year, including winter, clouds have a warming impact on the surface because they reduce the surface energy loss by reemitting longwave radiation back to the surface (Shupe and Intrieri 2004). The phase of the cloud condensate has a large impact on the radiative processes as liquid water in clouds more efficiently absorbs and reemits longwave radiation compared to frozen water (Shupe and Intrieri 2004). In winter, the air temperature is typically well below the freezing point and temperature changes do not often cause surface melt, but higher temperatures can reduce sea ice growth, resulting in thinner sea ice, which is also more vulnerable to melt in the following spring

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and summer (Screen and Simmonds 2010; Stroeve and Notz 2018).

The dramatic warming of the Arctic, known as Arctic amplification, and the sea ice concentration decline observed during the recent decades have been attributed to several feedback processes, such as lapse rate, surface albedo, and Planck feedbacks, but also to changes in large-scale circulation, atmospheric moisture transport and clouds (Graversen and Wang 2009; Doyle et al. 2011; Liu et al. 2012; Pithan and Mauritsen 2014; Park et al. 2015; Woods and Caballero 2016; Gong et al. 2017; Johansson et al. 2017; Gimeno-Sotelo et al. 2018; Pithan et al. 2018). Park et al. (2015) addressed causality of processes related to clouds and radiation based on 33 winters of ERA-Interim reanalysis data and satellite data. They showed based on lead-lag-time analyses that a positive anomaly in horizontal moisture transport and warm-air advection typically initializes an increase in the vertically integrated total column water and suppresses evaporation. Shortly afterward, an increase in downward longwave radiation follows, which affects sea ice. These findings were supported by Gong et al. (2017). Furthermore, reduced sea ice concentration in winter has been found to correlate in many locations with increased surface evaporation and upward latent heat flux (Screen and Simmonds 2010; Jun et al. 2016), and it has led to locally increased cloud formation and enhancement in longwave radiation toward the surface (Jun et al. 2016). This has strengthened the cloud-temperature-moisture relationship in the lower troposphere during the last decades (Morrison et al. 2019). From the above mentioned studies, it can be inferred that the sea ice-cloud interactions are presumably acting in two directions and causing a positive feedback loop in winter: an increased cloud cover may reduce sea ice concentration, which in turn may further increase cloud cover.

The importance of moisture transport for the cloud cover in the Arctic was already recognized by Curry and Herman (1985), who linked synoptic situation, moisture transport, and cloud cover and found the large-scale moisture transport to be important in the Beaufort Sea region, especially for midlevel cloud cover. In addition, Walsh and Chapman (1998) demonstrated a relationship between sea level pressure and cloud cover in the central Arctic. Moisture transport to the Arctic, cloud cover, and cloud water content have also been shown to be associated with the variations of the Arctic Oscillation (AO) (Eastman and Warren 2010; Devasthale et al. 2012; Jun et al. 2016). Recently, much research focus has been on moisture intrusions, which are narrow plumes of anomalously warm and moist air, typically accompanied by increased cloud amount and enhanced downward longwave radiation (Woods et al. 2013;

Johansson et al. 2017; Liu et al. 2018), penetrating to the Arctic. The intrusions are responsible for a major part of the moisture transport to the Arctic, and they are found to be associated with a dipole-like large-scale flow pattern with a blocking high to the east and an area of low pressure to the west (Skific et al. 2009; Woods et al. 2013; Liu and Barnes 2015). This dipolelike pattern enables a more meridional flow from midlatitudes to access the Arctic Ocean. Pithan et al. (2018) pointed out that notable airmass transformations take place along the path of intrusions, and in particular, phase changes from liquid water to frozen water are critical for the radiative effects of clouds and for cloud decay and dissipation. Most of the moisture transported to the Arctic has its origin in the Atlantic Ocean and the Pacific Ocean, especially in winter (Vázquez et al. 2016; Zhong et al. 2018), and the local moisture flux from the surface (i.e., evaporation) in the Arctic is estimated to provide only about 10% of the total column water vapor on a yearly basis (Boisvert et al. 2015).

Despite the inevitable importance of atmospheric moisture and clouds on the Arctic climate, their distributions, properties, and climate impacts are still poorly known, especially in winter. Previous studies, cited above, have contributed to understanding of the climatology of moisture and clouds in the Arctic, feedback processes related to moisture and clouds, intensive moisture intrusions, and, very recently, also the impacts of intensive moisture intrusions on clouds. However, most studies have been restricted to intensive events, certain circulation types, or patterns associated with the North Atlantic Oscillation (NAO) and AO only (Devasthale et al. 2012; Woods et al. 2013; Liu et al. 2018). This study intends to expand our knowledge on those topics by offering, for the first time, a systematic picture on how atmospheric large-scale circulation is related to moisture transport, distributions of moisture and clouds, and surface downward longwave radiation in wintertime in the current climate of the circumpolar Arctic. This is done by applying the self-organizing map (SOM) method (Kohonen 2001), which enables a comprehensive analysis of a large variety of atmospheric circulation regimes. In this study, anomaly distributions of atmospheric moisture transport, moisture, clouds, and downward longwave radiation are related to 30 characteristic wintertime atmospheric circulation regimes, which are allocated from 15 years (2003–17) of mean sea level pressure (MSLP) data applying the SOM method. The data are taken from an atmospheric reanalysis, ERA-Interim (Dee et al. 2011) of the European Centre for Medium-Range Weather Forecasts, which assimilates the existing observations into a numerical weather prediction model thereby offering a

gridded and coherent representation of circulation patterns, moisture, and clouds. We also give insights into regional and vertical distributions of the moisture and cloud variables in different circulation regimes. Furthermore, we demonstrate and discuss connections of moisture and cloud distributions and their anomalies to known climate indices, such as the NAO and AO, as well as to some other frequently occurring atmospheric circulation patterns. The results of this study provide a solid basis for further studies addressing changes and trends in atmospheric circulation and their influence on moisture and clouds in the Arctic.

2. Data and methods

a. ERA-Interim

In this study, gridded fields of mean sea level pressure, wind components, moisture, and cloud variables as well as downward longwave radiation at the surface were analyzed for winters [December–February (DJF)] during the period 2003–17 in the circumpolar Arctic north of 55°N. This 15-year-long study period represents “the new climate” of the Arctic, with decreased sea ice concentration and increased surface temperature and cloud cover (Jun et al. 2016). The analyses were based on ERA-Interim (Dee et al. 2011). ERA-Interim represents a state-of-the-art global atmospheric reanalysis. It applies a four-dimensional variational data assimilation method to assimilate a variety of observations, including, for example, radiosonde observations, satellite radiances, and infrared spectrometer observations from the Atmospheric Infrared Sounder (AIRS). The spectral model resolution of ERA-Interim is T255, and the data utilized in this study have a horizontal resolution of $0.75^\circ \times 0.75^\circ$. ERA-Interim has 60 vertical model levels, but, for simplicity, we only show results that are based on pressure-level data (except for vertically integrated products of ERA-Interim calculated directly on model levels). The pressure-level data are provided at a 25-hPa vertical interval from 1000 to 750 hPa and at a 50-hPa interval from 750 to 300 hPa. Our comparison of results based on model-level and pressure-level data supported this choice: results for horizontal moisture transport based on model-level data, with the mass correction method of Trenberth (1991) applied to correct erroneous mass fluxes associated with spurious winds, were practically the same as the results based on pressure-level data. This small difference between model- and pressure-level data has also been noticed by Dufour et al. (2016). The reanalysis output was analyzed at 6-h intervals. Most of the variables are available at 6-h intervals in the

reanalysis, but evaporation, divergence of horizontal moisture transport, and downward longwave radiation are not analysis variables and were taken from 6- and 12-h forecasts.

Whereas atmospheric humidity is assimilated in ERA-Interim, clouds are entirely modeled entities that are only indirectly constrained by assimilation of observations. The cloud parameterization scheme of ERA-Interim is based on the approach of Tiedtke (1993). ERA-Interim has two prognostic cloud variables: cloud fraction and cloud condensate. Partitioning of cloud condensate to liquid water and frozen water is diagnostically determined as a function of temperature. Cloud water is in the liquid phase when temperature is 0°C or higher. The fraction of frozen water monotonically increases (and the fraction of liquid water decreases) with decreasing temperature toward −23°C, and only frozen water can occur in the reanalysis in conditions with temperature below −23°C. It is, however, noteworthy that in observations from Alaska, northern Canada, and the western Arctic Ocean, liquid water has been found in clouds at temperatures as low as −40°C (Shupe 2011).

The accuracy of ERA-Interim data and its impacts on the results of this study are discussed in the online supplemental material. In summary, the accuracy of ERA-Interim can be considered to be sufficient when it comes to an investigation of relationships between atmospheric large-scale circulation and moisture/cloud distributions. The main focus of this study is on anomalies. Anomalies are considered to be more trustworthy than mean values (Liu and Key 2016), although anomalies are also liable to notable uncertainties in their response to large-scale circulation because of possible misrepresentation of physical processes related to clouds and turbulence in the reanalysis. We presume that the largest uncertainties in this study are related to cloud phases, and we are therefore careful not to draw conclusions too far on the basis of the cloud phase.

b. The self-organizing map method

Generalized atmospheric circulation patterns in the Arctic, obtained by applying the SOM statistical clustering method, form the core of this study. The SOM method was developed by Kohonen (2001), and it can be characterized as a nonlinear mapping of high-dimensional input data onto a two-dimensional array of reference vectors, that is, nodes. In other words, the method uses unsupervised learning to determine generalized patterns in data. The SOM method was originally developed for artificial neural networks, but it has been extensively applied in many fields of science, including since 2002 the climatology of synoptic patterns (Hewitson and Crane 2002). The first SOM study addressing the Arctic

was published by [Cassano et al. \(2006\)](#) who derived a synoptic climatology for the Arctic from an ensemble of twentieth- and twenty-first-century climate simulations. More recently, SOMs have been utilized to, for example, assess future changes in meridional moisture transport across 70°N ([Skific et al. 2009](#)) and to classify atmospheric moisture transport pathways in the vicinity of Greenland Ice Sheet ([Mattingly et al. 2016](#)). The SOM method is a statistical method, not a physical-based method, but it has demonstrated its ability to cluster similar pressure patterns in a physically meaningful way in previous studies.

In this study, the method provides a two-dimensional array of gridded MSLP fields, which have the main characteristics of the input MSLP data. The method preserves the probability density of the input data by allocating more nodes to more frequent patterns in the input data ([Cassano et al. 2006](#)). The size of node array is often subjectively determined by the user. The size depends on the application; fewer nodes will lead to a high level of generalization of the patterns but make the visualization and conceptualization of the results easier, whereas more nodes will increase the level of details and amount of regional features in the patterns ([Hewitson and Crane 2002](#)).

First, an initial array of reference vectors is created by the SOM algorithm procedure. Each node has an associated reference vector that has equal dimensions to the input data. For example, if the input data are a time series in a two-dimensional spatial grid of 50×50 , each node will have a reference vector consisting of 2500 values. The initialization can be made in several ways, but in this study, we applied the random initialization scheme, in which the initial reference vectors are randomly selected. Second, during the training each data vector constituted by each time step of the input data is compared with the reference vector of each node. Depending on the similarity between the data and reference vectors, measured as the Euclidian distances, the reference vectors of the SOM are adjusted toward the data vectors. The node having the most similar reference vector to a data vector is adjusted most, and the nodes around it, within a user-defined radius, are also adjusted but to a lesser degree depending on their distance from the most-adjusted node ([Cassano et al. 2006](#)). The degree of adjustment is defined by a user-defined learning-rate parameter. The procedure is repeated until the Euclidian distances of reference vectors to the input data do not change and are hereby minimized. Last, reference vectors become ordered despite the fact that they were initially randomly distributed. In the resulting SOM array, similar patterns are located close to each other whereas dissimilar patterns are located far

apart. Each time step of the input data can then be associated with the most similar node based on the Euclidian distance.

In this study, the SOM method was applied to 15 years (2003–17) of wintertime (DJF) MSLP data of ERA-Interim at 6-h intervals. To ensure equal weighting in the whole study region, the MSLP data were first re-gridded to an equal-area grid. Based on a subjective evaluation, 5×6 array of nodes was selected as the most appropriate to represent wintertime atmospheric circulation patterns in the Arctic. It was found that as many as 30 different circulation regimes were needed to adequately resolve details of different circulation patterns because much of the horizontal moisture transport is typically driven by narrow, filamentary moisture intrusions. Moisture, cloud, and radiation variables were associated with circulation regimes on the basis of their time steps, and anomalies were calculated by combining the time steps belonging to a certain node. The anomalies were calculated by subtracting the gridpoint mean values for the time steps belonging to a certain node from the gridpoint mean values for the whole time series.

c. Horizontal moisture transport

In addition to variables available in ERA-Interim, we also show results for horizontal moisture transport. Horizontal moisture transport, calculated on each pressure level of ERA-Interim from the surface to 300 hPa, was divided into meridional transport

$$f_v = qv \quad (1)$$

and zonal transport

$$f_u = qu, \quad (2)$$

where q is specific humidity, v is meridional wind component, and u is zonal wind component. Vertically integrated moisture transport from the surface to the 300-hPa level F_v was obtained for the meridional component in a discrete form as follows:

$$F_v = \int_{p_{\text{surface}}}^{300\text{hPa}} \frac{1}{g} qv dp \approx \sum_{i=1}^{n-1} \frac{1}{2g} (q_i v_i + q_{i+1} v_{i+1}) (p_i - p_{i+1}), \quad (3)$$

where p is air pressure, g is the gravitational acceleration, and subscript i refers to the index of each pressure level ($i = 1$ corresponds to the surface). Levels below the surface were not included in the calculations; the levels were removed from the analysis if the pressure at the level was higher than the actual surface pressure at that particular time step. Below the lowest pressure level (located above the surface), the flux density of the

lowest pressure level was used for the layer between that level and the surface. The zonal component of the vertically integrated moisture transport was calculated by replacing v with u in Eq. (3). Following Naakka et al. (2019), who stated that northward and southward transports partly compensate each other in the net horizontal transport, we also show results for the total moisture transport. The total meridional transport is defined as a mean of the absolute values of the instantaneous meridional transports, and it therefore better represents the actual moisture transport taking place without the impact of compensation.

When anomalies of moisture, cloud, and radiation variables were associated with circulation regimes of SOM, statistical significance of these anomalies was tested by applying a Monte Carlo approach. This was done by constructing 5000 random subsets of a given field from the original data and comparing anomalies in the random subsets to the anomalies in the SOM nodes. The subsets had the same number of samples as the SOM nodes. Then, a two-tailed test was performed. In a given grid point, if less than 1% of the anomalies in the random subsets were higher than the anomaly in the original SOM node or less than 1% of the anomalies in the random subsets were lower than the anomaly in the SOM node, the anomaly was different from zero at the 98% significance level. For regional anomalies, the Monte Carlo approach was applied to regionally averaged anomaly values, instead of gridpoint values, but the principle was otherwise the same. Regionally averaged anomalies are shown for six subregions: 1) the Arctic Ocean, 2) the North Atlantic, 3) northern Europe, 4) Siberia, 5) Alaska and Canada, and 6) Greenland (Fig. 1). The division of regions is adapted from Naakka et al. (2018), who defined them on the basis of spatial patterns of specific humidity.

d. Circulation indices

The circulation patterns, as well as moisture and cloud variables, were related to indices of the AO and NAO and to the Greenland blocking index (GBI), as well as to a frequently occurring pressure pattern, described in section 3b. The AO is the leading empirical orthogonal function of wintertime sea level pressure field. It is a large-scale mode of climate variability in the Northern Hemisphere that displays an opposing pattern of pressure between the Arctic and the midlatitudes (Thompson and Wallace 1998). In the negative phase of the AO, the zonal flow is weaker than usual and the meridional flow is enhanced, whereas the positive phase is associated with a relatively strong zonal flow. The NAO, in turn, consists of a north–south dipole of pressure anomalies between the Azores subtropical high and the Icelandic

FIG. 1. Map of subregions.

subpolar low (Barnston and Livezey 1987). The positive phase of the NAO is associated with a northward shift of North Atlantic storm tracks whereas the negative NAO phase is associated with weaker westerly winds. The NAO correlates to a high degree with the AO. In this study, daily values of the AO and NAO were obtained from the websites of Climate Prediction Center of National Oceanic and Atmospheric Administration (NOAA) (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml and <http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>). GBI is a measure of blocking in Greenland, defined as the mean 500-hPa geopotential height for the 60°–80°N, 20°–80°W area, and it emphasizes more the northern center of the NAO dipole pattern (Hanna et al. 2013). Daily values of GBI were obtained from Earth System Research Laboratory of NOAA (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/GBI_UL). All daily index values were linearly interpolated to 6-h intervals to associate them with the SOM regimes of the same time intervals.

3. Results

a. Mean distributions of moisture and clouds

In this section, an overview of mean moisture and cloud distributions in the Arctic in winter (2003–17) is given. These results will enable relating the anomalies

FIG. 2. Winter (December–February) mean (a) low cloud cover ($1.0 > \sigma > 0.8$), (b) medium cloud cover ($0.8 \geq \sigma > 0.45$), and (c) high cloud cover ($0.45 \geq \sigma$) in ERA-Interim (2003–17). The σ values in the parentheses indicate the definitions of the clouds on the basis of their altitudes, σ being the pressure divided by the surface pressure. Also shown are regional cloud fraction occurrence distributions of (d) low, (e) medium, and (f) high clouds. Definitions of the regions are shown in Fig. 1.

presented in section 3c to mean values of the variables.

According to ERA-Interim, the Arctic is generally cloudy in winter, and especially the low-level cloud fraction is high (Figs. 2a–c). The regional differences in cloud fraction at low, medium, and high levels are not dramatic, but the mean fields hide a bimodal cloud fraction distribution, peaking at clear-sky (fraction < 0.1) and overcast conditions (fraction > 0.9) (Figs. 2d–f). Overcast conditions are most common at the low level. Clear-sky conditions are most common at the medium and high levels where their occurrence is approximately 50%.

Interestingly, mean spatial distribution of cloud water in winter (Figs. 3a–c) does not resemble the spatial distribution of cloud fraction (Figs. 2a–c), but rather resembles the mean distribution of water vapor (Fig. 3d). The spatial maxima of vertically integrated total cloud water are found in the North Atlantic and the Gulf of Alaska, particularly in the vicinity of high orography. In the Arctic Ocean, Siberia, North America, and Greenland, the water vapor and cloud water content are

relatively low and the cloud condensate mainly occurs in the frozen phase in ERA-Interim. The mean spatial distribution of total cloud water (Fig. 3c) is, to some extent, also similar to the distributions of net meridional moisture transport (Fig. 3f) and evaporation (Fig. 3e); evaporation has its maxima in the ice-free ocean areas, whereas meridional moisture transport peaks are more defined to the North Atlantic and the Gulf of Alaska.

Mean vertical profiles of moisture and cloud variables have notable regional variability, but the mean profiles of different variables seem to be connected to each other in a similar way in all of the regions (Fig. 4). The shapes of specific humidity profiles are very similar to the profiles of total meridional moisture transport (the sum of absolute northward and southward transports), having the vertical maximum at the same level as the total meridional transport or, at the most, 50 hPa lower. Humidity inversions, that is, layers in which the specific humidity increases upward, are visible in the profiles of specific humidity, except in the North Atlantic, where the specific humidity maximum is at the surface, presumably due to large evaporation from the sea surface in

FIG. 3. Winter (December–February) mean (a) vertically integrated cloud liquid water, (b) vertically integrated cloud frozen water, (c) vertically integrated total cloud water, (d) vertically integrated water vapor, (e) evaporation, and (f) net moisture transport in 2003–17. In (f), meridional net transport is indicated with colors, and the vectors denote the meridional and zonal net transport.

this region. On one hand, the specific humidity maxima aloft are at least partly a cause of vertically uneven horizontal moisture transport, with the maximum between 900 and 800 hPa; on the other hand, the specific humidity inversion probably contributes to the vertical profile of the moisture transport maintaining its elevated maximum. Due to compensating effects of northward and southward transport, the net meridional moisture transport profiles have less pronounced variability with height than the total transport. Cloud water basically peaks at the same altitude as the total moisture transport and specific humidity, except in the North Atlantic where the large sensible heat flux from the warm ocean leads to efficient mixing in the boundary layer, reducing the relative humidity near the surface but leading to condensation higher in the well-mixed layer. Profiles of cloud fraction have independent characteristics and do not directly match with the moisture and cloud water profiles. Large spatial variability in both horizontal and vertical directions is also evident in cross sections of

cloud water content at 60° and 70°N (Fig. 5). Cross sections of net moisture transport in ERA-Interim are not shown here because they have previously been presented by Naakka et al. (2019) (in their Fig. 10) nearly for the same period (2003–14). The general characteristics of cross sections of net moisture transport and cloud water content are similar. For example, large amounts of cloud water occur in a high column in the North Atlantic and the Gulf of Alaska, in areas where the net meridional moisture transport is also large according to Naakka et al. (2019). High mountains act as division lines for moisture transport and cloud water content and alter the height of cloud water maximum. An example of this can be seen at 60°N in Fig. 5c, in which cloud water in the North Atlantic (from 45°W to 0°) occurs over a large vertical range having the maximum around the 850-hPa level, whereas the cloud water maximum on the eastern side of the Norwegian mountains (from 20° to 60°E) is located 75 hPa lower. At 70°N, most of the cloud water is found between 30°W and

FIG. 4. Vertical profiles of regionally averaged (left) meridional moisture transport, (left center) specific humidity, (right center) cloud water, and (right) cloud fraction in winter (December–February). The blue solid line of meridional moisture transport shows the net meridional moisture transport, and the red dashed line shows the total meridional moisture transport (the sum of absolute northward and southward transports). The total cloud water is shown with a black solid line, the frozen cloud water is shown with a red dashed line, and liquid cloud water is shown with a blue dashed line. Note that the scale is different for the North Atlantic and northern Europe relative to other regions.

FIG. 5. Cross section of (a),(d) cloud liquid water content, (b),(e) cloud frozen water content, and (c),(f) total cloud water content on latitudes (top) 60° and (bottom) 70°N in winter (December–February).

90°E, across the Greenland and Norwegian Seas and parts of northern Europe. Liquid cloud water is mostly limited to levels below 800 hPa.

b. Large-scale circulation regimes

Wintertime atmospheric circulation in the Arctic was condensed to 30 types of circulation regimes applying the SOM method (section 2b). Each time step of our data is designated to one of these circulation regimes. The circulation types are presented in a 5×6 array in which the most similar regimes are located close to each other. The array of the characteristic MSLP patterns is shown in Fig. 6, and corresponding array of MSLP anomaly patterns is shown in Fig. S1 in the online supplemental material. Note that the MSLP patterns shown in Fig. 6 and Fig. S1 are the mean values of MSLP over the time steps belonging to each node, and hence they are not the reference vectors directly provided by the SOM algorithm. The relatively small difference (root-mean-square difference of 10 hPa) between the node-mean MSLP patterns and the reference vectors provided by the SOM method is an indicator that the regimes provided by the SOM algorithm are representative statistical constructs, which are not overly generalized.

All of the circulation regimes have at least 76 samples (i.e., 1.4% of the time steps) in them (Fig. 6). The corner circulation regimes 26 and 5 as well as regime 15 are the most common ones. The nodes 5 and 15 are characterized by anomalously low pressure in northern Eurasia, whereas regime 26 is characterized by anomalously high

pressure in most of the Arctic. Regime 30, with anomalously high pressure in northern Europe and western parts of Russia, is clearly the most persistent regime with its mean persistence of 3.8 days. In all of the regimes, transitions from one regime to another most commonly take place between the neighboring or diagonally closest regimes in the array.

Mean values of AO and NAO indices for each SOM node are shown in Figs. 7a and 7b. The circulation regimes in the three uppermost lines of the SOM array (nodes 1–15) are mostly associated with positive phases of these modes, whereas the corner node 26 and nodes around it are associated with negative phases of AO and NAO. In the circulation regimes linked with positive AO and NAO, the MSLP field is characterized by anomalously low pressure in one or several areas in the subpolar latitudes, typically in the North Atlantic and/or where the Aleutian low is reaching far north (Fig. 6 and Fig. S1). In negative phases of AO and NAO, positive anomalies of MSLP occur in most of the Arctic, especially in the Arctic Ocean, northern Eurasia, and Greenland. GBI is strongest in negative phases of AO and NAO, but also when the subpolar low pressure in the European sector is relatively weak or located far to the east from Greenland (in the rightmost column of the array) (Fig. 7c).

In addition to the abovementioned indices, we define the “Arctic bridge” on the basis of a frequently occurring circulation pattern that has clear impacts on the moisture and cloud distributions in the Arctic. The Arctic bridge is qualitatively defined here as a continuous high

FIG. 6. Mean sea level pressure averaged over the cases belonging to each of the SOM nodes in the winters (December–February) of 2003–17. Relative frequency (of the 5416 total cases) and mean persistence of each node are shown in the parentheses.

FIG. 7. Mean values of the (a) NAO, (b) AO, and (c) GBI, and (d) characterization of the existence and strength of the Arctic bridge in the SOM nodes.

pressure area reaching from Siberia to North America through the Arctic Ocean, with no isobars crossing from the Atlantic sector to the Pacific sector. The Arctic bridge prevents a flow from the Atlantic sector to reach the Pacific. The Arctic bridge is present in 22 of the circulation regimes, and its strength in those circulation regimes is subjectively evaluated from Fig. 6 to be either strong or weak (Fig. 7d). Occurrence of the Arctic bridge is not directly linked to the indices of AO and NAO or that of GBI.

c. Linkages to moisture, clouds, and downward longwave radiation

Relationships between large-scale circulation regimes and moisture and cloud properties are evident. To illustrate this, anomalies of horizontal moisture transport, water vapor, cloud water, and downward longwave radiation at the surface are shown in Fig. 8 for four regimes (1, 5, 26, and 30). Corresponding distributions of divergence of the horizontal moisture transport, anomalies of evaporation and medium-level cloud fraction in the same four SOM nodes are shown in Fig. S2 in the online supplemental material. These regimes are located in the corners of the SOM and hence, they represent the most different circulation regimes, which are also among the most common ones. The four example regimes demonstrate the general relationships between variables, which are also commonly found in the other circulation regimes. Most of the anomalies related to different circulation regimes, and discussed in the following paragraphs, are statistically significant at

98% level, which is indicated in the figures. In addition, anomalies of horizontal moisture transport, cloud water, and downward longwave radiation in all of the 30 circulation regimes are shown in the online supplemental material (Figs. S3–S5) to provide detailed information on different circulation types and their regional impacts.

The circulation of regime 1 is characterized by anomalously high pressure over Alaska, anomalously low pressure in the western part of North Atlantic, and a presence of strong Arctic bridge, and it is linked to the positive phase of NAO and AO (Fig. 6, Fig. S1, and Fig. 7). As seen in Fig. 8, this circulation pattern enables increased meridional moisture transport in the regions where the zonal pressure gradients are large, resulting in enhanced northward moisture transport in the North Atlantic and around the Bering Strait, and strong negative anomaly in the transport in the western parts of the North America and on the coasts of Greenland. In this circulation type, moisture is simultaneously transported to the central Arctic both from the Atlantic and Pacific Ocean, and these two moisture paths are separated by the Arctic bridge. In the two regions of anomalously strong northward moisture transport, the vertically integrated water vapor has also anomalously high values. Impacts of the zonal moisture transport component can also be seen, especially in Alaska and on the east side of Greenland. On one hand, the high water vapor is a consequence of increased moisture transport to the area, while, on the other hand, it is the high water vapor content that enables the large moisture transport to take place in the area. Evaporation, in turn, has negative

FIG. 8. Anomalies of mean (left) vertically integrated moisture transport (vectors show the anomaly of zonal and meridional transport whereas the colors show the anomaly of meridional transport only), (left center) vertically integrated water vapor, (right center) vertically integrated cloud water content, and (right) downward longwave radiation at the surface in four SOM nodes. Dotted shadings show the anomalies that are different from zero at the 98% significance level (not shown for anomaly of moisture transport because of the vectors in the plot).

anomalies in the regions where there is a high amount of water vapor and large northward transport (Fig. S2), which is presumably explained by the reduction of evaporation when the air above the surface is relatively moist.

In regime 1, anomalies of cloud water are to a large extent collocated with those of water vapor, although the cloud anomalies show more small-scale variability in space. A closer look at the east coast of Greenland

FIG. 9. Anomalies of (left) meridional moisture transport and (right) cloud water at cross sections along 70°N in four SOM nodes. Dotted shadings show the anomalies that are different from zero at the 98% significance level.

shows that there is a pronounced positive cloud water anomaly, mainly in the frozen phase, which has a large vertical extent reaching nearly from the surface to 700 hPa (Figs. 8 and 9). Thus, Greenland is acting as a cold barrier for transported moisture, which leads to enhanced condensation and amounts of cloud water on the coast (via water vapor convergence, shown in Fig. S2, condensation due to lifting of the air mass, and impacts of the cold surface of Greenland), and a similar effect of Greenland is seen in all of the SOM nodes in which the flow has a perpendicular component toward the coast of Greenland. The match between moisture convergence and cloud water is also very good in the Pacific sector (Fig. 8 and Fig. S2).

In the vertical direction, anomalies of meridional moisture transport and cloud water are not exactly collocated (Fig. 9); cloud water anomalies have maxima higher up in the atmosphere than the meridional moisture transport, reflecting an influence of the vertical profiles of temperature on cloud condensation. Medium cloud cover anomaly field (Fig. S2) resembles the cloud water distribution, but the cloud cover anomalies are weaker and less commonly statistically significant. Low-level cloud cover is mostly independent from the cloud water distribution (not shown). The anomaly field of downward longwave radiation at the surface is almost directly a composite of water vapor and cloud water anomaly fields (Fig. 8), although temperature of the

air masses also influences the downward longwave radiation.

The circulation in regime 5 is characterized by anomalously high pressure over North America, anomalously low pressure in all of Eurasia, the positive phase of AO and NAO, and the existence of weak Arctic bridge (Fig. S1 and Fig. 7). In most of Eurasia, the flow is very zonal, and in the northern part of the North Atlantic, the meridional component of moisture transport is directed southward, prohibiting moisture transport from the North Atlantic toward higher latitudes. Thus, moisture transport to the Arctic is mainly taking place through the area of the Bering Strait. The vertically integrated water vapor is anomalously high in the vicinity of Bering Strait, linked to the large moisture transport. Evaporation has a positive anomaly in the North Atlantic, that is, in the same region with large negative anomalies of meridional moisture transport and water vapor (Fig. S2). It is noteworthy that the flow in this region, and not only its anomaly, is directed southward and hence the moisture provided by evaporation is transported toward lower latitudes. This is practically the case for positive anomalies of evaporation in all of the circulation regimes, so that anomalously high evaporation is linked to a southward flow. Anomalies of vertically integrated cloud water and downward longwave radiation resemble the water vapor anomaly distribution, but, in addition, show a small area with a pronounced positive anomaly on the west coast of Norway due to convergence of horizontal moisture transport (Fig. S2). Interestingly, the negative anomaly of cloud water in the North Atlantic is not associated with a reduced medium (or low) cloud cover in this region (Fig. S2).

The dominating feature in the circulation in regime 26, the most frequent of all the regimes, is an anomalous high pressure situated over the central Arctic and Greenland (Fig. 6 and Fig. S1). This extensive high pressure drastically reduces the meridional moisture transport to high latitudes. This circulation type also causes a large negative anomaly for zonal transport, although the zonal transport is still weakly eastward at most of the longitudes along 60°N. The regime is associated with the largely negative AO and NAO, strong Arctic bridge, and it has the highest GBI of all the regimes (Fig. 7). Regime 26 is one of the circulation regimes in which the northward moisture transport is strongest on the west side of Greenland. This northward transport is presumably causing statistically significant positive anomalies of water vapor, cloud water and downward longwave radiation in the region and farther north (Fig. 8 and Fig. S3). In the North Atlantic and most of northern Eurasia, the regime is linked to large

negative anomalies in moisture transport, water vapor, cloud water, and downward longwave radiation but not in low and medium cloud cover. This statistically significant negative anomaly of cloud water content reaches at least up to 300 hPa (Fig. 9).

Circulation regime 30 is characterized by anomalously high pressure over Eurasia and weak negative pressure anomalies over North America and the Canada basin (Fig. 6 and Fig. S1). This circulation regime has clearly the highest persistency of all the regimes (Fig. 6). The regime is associated with the negative AO but positive NAO, and, importantly, it is one of the eight regimes in which the Arctic bridge does not exist (Fig. 7). The lack of Arctic bridge has large impacts on moisture and clouds, especially at latitudes north of 70°N, as it allows the horizontal moisture transport from the North Atlantic to the North Pole and farther toward the Bering Strait. In some of the circulation regimes, like in 19 and 24, the moisture from the North Atlantic flows over the pole all the way to the Bering Strait (Fig. S3). In regime 30, however, moisture is transported along the large pressure gradient toward the Barents, Kara, and Laptev Seas (Fig. 8), from where this moist air mass is moving back toward lower latitudes, seen as a negative anomaly of meridional moisture transport. The horizontal path of the moisture is associated with positive anomalies in water vapor, cloud water, and downward longwave radiation, and anomalously little evaporation (Fig. 8 and Fig. S2). Along this path, phase changes occur from liquid to frozen water. An indication of these phase changes is that positive anomalies of liquid water in regime 30 are mainly limited to the North Atlantic, whereas positive anomalies of frozen water are found farther along the path, over the central Arctic Ocean as well as over Barents, Kara, and Laptev Seas (not shown). Direct impacts of the high pressure, presumably related to the potential drying effect of large-scale subsidence and lack of efficient moisture transport, are seen in northern Europe and the western part of Russia as an anomalously low water vapor content, cloud water content, medium- and high-level cloud cover, and downward longwave radiation (Fig. 8 and Fig. S2).

Relationships between moisture and cloud variables and the circulation regimes do not directly indicate causality. To further address how moisture anomalies progress in time, time lead and lag were investigated in the circumpolar Arctic between 70° and 80°N, by setting the start time of each circulation regime to zero at the day this circulation regime occurs. Time lag for anomaly of vertically integrated water vapor is shown in Fig. 10 for the four corner circulation regimes. Results for cloud water were qualitatively similar but had more

FIG. 10. Anomaly of vertically integrated water vapor, averaged between 70° and 80°N, as a function of longitude and time lag in four SOM nodes. Positive values of time lag denote time elapsed since the start of a circulation regime (node). Dotted shadings show the anomalies that are different from zero at 98% significance level.

small-scale variability in time and space (not shown). In regime 1, the positive water vapor anomaly in the North Atlantic is mainly initiated by the regime, which is indicated by the maximum for positive time lags. The magnitude of the positive anomaly stays nearly constant for the following 72 h, and spreads in the zonal direction with time. The positive anomaly around the Bering Strait in regime 1 and the positive anomaly in the North Atlantic in regime 30 are typically not initiated but rather intensified by these regimes. This manifests that these regimes typically occur after a regime that is also related to positive, but weaker, anomalies in the region; most commonly regime 6 with a strong positive anomaly in the Bering Strait precedes regime 1, and regime 29 with a positive anomaly in the northern part of the North Atlantic precedes regime 30 (not shown). The negative anomalies in the North Atlantic in regimes 5 and 26 are drastically intensified after the start of these regimes, although the typically preceding regimes are also linked to negative anomalies in the region. The time lag analyses suggest that the anomalies of water vapor (and cloud water) are responding to atmospheric circulation, but confirming the actual causality would require,

for instance, some sensitivity experiments with a numerical model.

Regional impacts of the circulation regimes are illustrated with regional anomaly arrays for the meridional moisture transport, as well as vertically integrated water vapor and cloud water (Fig. 11). The region definitions are shown in Fig. 1. Positive and negative anomalies are clustered in the arrays, but positions and orientations of these clusters naturally vary from region to region, because each region has individual pressure patterns as a part of a circulation regime. Impacts of the AO and NAO are directly seen in the anomaly arrays of northern Europe and Greenland, but in opposite ways. In northern Europe, circulation regimes related to the positive (negative) AO and NAO are associated with positive (negative) anomalies of meridional moisture transport, water vapor and cloud water, but in Greenland the positive AO and NAO are linked with negative anomalies of these variables. In Siberia, positive moisture and cloud anomalies are typically associated with negative anomalies in the regional MSLP. In the North Atlantic, circulation regimes situated diagonally, from regime 1 to 30, in the array are associated with positive moisture and cloud anomalies. A common denominator for these diagonally situated

FIG. 11. Regionally averaged anomalies of (left) moisture transport, (center) vertically integrated water vapor, and (right) cloud water in the different circulation regimes (SOM nodes marked with 1–30). Anomalies that are different from zero at the 98% significance level are circled.

regimes is the northward-directed flow in the North Atlantic, but otherwise these regimes differ largely.

4. Discussion and conclusions

The largest anomalies of moisture transport related to certain circulation regimes are as large as the mean net moisture transport itself. In addition, anomalies of water vapor are often up to $\pm 3 \text{ kg m}^{-2}$, and anomalies of cloud water up to 80 g kg^{-1} , which are in many regions comparable to the mean values of these variables (Fig. 3). Anomalies of downward longwave radiation are in many circulation regimes up to $\pm 50 \text{ W m}^{-2}$, which may strongly influence the surface temperature. It is important to acknowledge the large uncertainties, especially in cloud water and downward longwave radiation, which may affect the anomalies but are estimated to be smaller in magnitude than the anomalies reported (see the online supplemental material). Effects of large-scale circulation on spatiotemporal distributions of water vapor, cloud water, and longwave radiation in the Arctic are to a large extent occurring through the impact of horizontal moisture transport. In the horizontal direction, distribution of moisture transport largely defines the distributions of water vapor and cloud water. Convergence of moisture transport influences the spatial distributions of cloud water mainly when the flow has a component toward a high orography, causing positive anomalies of cloud water, reaching high altitudes over the coasts of Greenland, Norway, and Alaska. It appears that relatively weak convergence can lead to an anomalously large amount of cloud water; it seems that it is enough to have a positive anomaly in water vapor and a sufficient amount of convergence. Furthermore, anomalies in moisture transport and moisture convergence are not totally independent. Theoretically moisture transport occurs along moist isentropes, which typically are tilted upward toward the north and hence moisture transport commonly occurs with upward motion of air leading to enough moisture convergence to form clouds. In the vertical direction, cloud water distribution is shaped by the profiles of both moisture transport and temperature. In high pressure regions, the absence of effective moisture transport (together with subsidence, which can potentially further dry the air) is seen as negative anomalies of specific humidity, cloud water content, and downward longwave radiation. On one hand, the results emphasize the importance of horizontal moisture transport in the climate system of the Arctic in winter, as also indicated in several previous studies, for example, by Curry and Herman (1985), and Liu et al. (2018). On the other hand, cloud cover, in particular low-level cloud cover, in ERA-Interim, seems to match

poorly with the moisture, cloud water, and downward longwave radiation distribution, which might depend on the parameterization of the physical processes and model resolution. Hence, thin, even uniform, cloud cover can be associated with a variety of meteorological situations, whereas anomalously high cloud water content is typically dependent on the moisture transport. Especially, the poor match between the anomalies of low clouds and downward longwave radiation at the surface is rather surprising, because the low cloud cover typically has a larger radiative influence on the surface than the mid- and high-level clouds.

Evaporation is a source of moisture over the partially ice-free oceans in winter, but it is typically not efficient enough to shape the large-scale distributions of specific humidity and cloud water in the synoptic scale. Positive anomalies in evaporation are found when the flow is directed southward (typically associated with cold-air outbreaks), meaning that much of the moisture provided by the evaporation taking place in the Arctic is in fact transported southward, and not toward higher latitudes. Evaporation may still be very important in winter for Arctic clouds locally (Curry et al. 1996), and long-term changes in evaporation have been reported to have an impact on cloud formation and longwave radiation (Jun et al. 2016).

Many of the impacts of large-scale circulation on moisture, clouds, and longwave radiation are associated with frequently occurring large-scale pressure patterns. Previously, Groves and Francis (2002) have reported larger northward moisture transport across 70°N over the Atlantic sector and larger southward moisture transport over the Canadian Archipelago when the AO is strongly positive. Devasthale et al. (2012) has reported a similar dipole structure in cloud fraction anomalies eastward and westward of Greenland, shifting between the opposite states depending on the sign of AO. Our results are in line with these previous findings but provide more comprehensive evidence on the impacts of AO on cloud distributions through various atmospheric circulation patterns and their associated moisture transport. Similarly to the previous studies, our results indicate that in northern Europe and the eastern North Atlantic, circulation regimes related to the positive (negative) AO are typically associated with positive (negative) anomalies of meridional moisture transport, water vapor and cloud water. In the western North Atlantic, Greenland, and the Canadian Archipelago the positive AO is linked to negative anomalies of these variables. We also show a similar dipole structure in relation to the NAO. However, our study also shows that a single value of NAO/AO index can hide very different circulation patterns, which in turn have large impacts on the

regional moisture transport in the Arctic. For example, positive phases of the AO and NAO include commonly occurring circulation regimes in which the dipole structure in the North Atlantic is not present, but, instead, the meridional transport is anomalously positive around the Bering Strait, as in the circulation regime 5 (Figs. 6 and 8). Except for studies addressing the reasons for the sea ice minimum in summer 2007 (L'Heureux et al. 2008; Graversen et al. 2011), the strong meridional transport from the Pacific has received less attention than transport from the Atlantic sector. Strong Greenland blocking, in turn, typically causes a positive anomaly in water vapor, cloud water and downward longwave radiation in the southwest of Greenland and negative anomalies in these variables in the North Atlantic.

In this study, we qualitatively defined a frequently occurring circulation pattern, the Arctic bridge, which is a continuous high pressure pattern reaching from Siberia to northern America through the Arctic Ocean. The Arctic bridge prevents a flow from the Atlantic to reach the Pacific sector. If the Arctic bridge does not exist, horizontal moisture transport from the North Atlantic across the central Arctic Ocean may occur, and positive anomalies of specific humidity, cloud water, and downward longwave radiation are often seen near the North Pole and along the path of the flow toward the Bering Strait. Especially, the results suggest that those circulation regimes lacking the Arctic bridge are subjected to a long fetch over the sea ice and long exposure for effective radiative cooling at high latitudes, which presumably leads to airmass modification and phase changes along the flow; these phase changes in clouds have been indicated as very important for radiative effects of clouds and for cloud decay and dissipation (Pithan et al. 2018).

Our results reveal a high dependence of moisture and cloud variables on atmospheric pressure fields, which appears important in the climate change perspective. In the future, changes in pressure fields, for example, related to the sea ice loss (Screen et al. 2018), could potentially largely modify the moisture transport in the Arctic, and thereby also modify regional distributions of water vapor, cloud water, and downward longwave radiation, at least regionally. Sea ice loss could possibly modify the frequency and duration of certain circulation patterns, and hence also the moisture transport related to each circulation pattern. For the net moisture flux across 70°N during the twenty-first century, it has been suggested that the projected increase will be more attributed to factors related to thermodynamic effects rather than changes in the circulation patterns (Skific et al. 2009). Projections on future changes in the Arctic clouds have remained as a major challenge for the scientific community; different modeling studies have

yielded contrasting results (Vavrus et al. 2012; Koenig et al. 2013). This study emphasizes that future changes in Arctic clouds are to be expected in connection with the projected enhanced meridional moisture transport into the Arctic.

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