Synoptic Conditions, Clouds, and Sea Ice Melt Onset in the Beaufort and Chukchi Seasonal Ice Zone

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ABSTRACT

Cloud response to synoptic conditions over the Beaufort and Chukchi seasonal ice zone is examined. Four synoptic states with distinct thermodynamic and dynamic signatures are identified using ERA-Interim reanalysis data from 2000 to 2014. CloudSat and CALIPSO observations suggest control of clouds by synoptic states. Warm continental air advection is associated with the fewest low-level clouds, while cold air advection generates the most low-level clouds. Low-level clouds are related to lower-tropospheric stability and both are regulated by synoptic conditions. High-level clouds are associated with humidity and vertical motions in the upper atmosphere. Observed cloud vertical and spatial variability is reproduced well in ERA-Interim, but winter low-level cloud fraction is overestimated. This suggests that synoptic conditions constrain the spatial extent of clouds through the atmospheric structure, while the parameterizations for cloud microphysics and boundary layer physics are critical for the life cycle of clouds in numerical models. Sea ice melt onset is related to synoptic conditions. Melt onsets occur more frequently and earlier with warm air advection. Synoptic conditions with the highest temperatures and precipitable water are most favorable for melt onsets even though fewer low-level clouds are associated with these conditions.

1. Introduction

How atmosphere and sea ice interact depends on the prevailing weather, which can be characterized by the synoptic condition. Stramler et al. (2011) report that during the wintertime of the Surface Heat Budget of the Arctic (SHEBA) field campaign (Uttal et al. 2002), there were two preferred states of surface and atmospheric conditions with distinct signatures in the surface net longwave radiative fluxes: a warm and opaquely cloudy state with low surface pressure, and a cold and radiatively clear-sky state with high surface pressure. The transition between the two states demonstrates, from a local perspective, the influence of the passing baroclinic wave on the surface. Over a larger spatial domain, the differences in the spatial configuration of synoptic-scale patterns, such as the Arctic cyclones and anticyclones, translate the local preferred states into different spatial patterns of atmospheric conditions, cloud distribution, and impacts at the surface. For example, the interaction between midlatitude cyclones and large-scale blocking patterns is related to the advection of warm and moist air masses into the Arctic in narrow filaments; downwelling longwave radiative fluxes at the surface increase significantly during these episodic moisture intrusion events (Doyle et al. 2011; Woods et al. 2013). During these moisture intrusion events, both the downwelling longwave radiation and the wind-induced sea ice drift contribute to decreases in sea ice concentration (Park et al. 2015a).

The role of synoptic conditions on clouds and sea ice in the Arctic is the focus of several recent studies. Using Defense Meteorological Satellite Program (DMSP) imagery from 1979 and 1980, Barry et al. (1987) report a connection between Arctic cloudiness and eight synoptic sea level pressure patterns. Müllennstädt et al. (2012) identify four distinct synoptic regimes that are associated with well-known synoptic features such as the Aleutian low and the Beaufort high. They report significant differences in the observed and retrieved cloud properties at Barrow, Alaska, under these four synoptic regimes. Using a different classification strategy, Barton et al. (2012) investigate the relationships between clouds and lower-tropospheric stability, and the cloud responses to the presence of sea ice under different
synoptic regimes. The covariance between the Arctic sea ice and clouds under these synoptic regimes is further examined by Taylor et al. (2015). Mills and Walsh (2014) explore the connection between sea ice and the interannual variability of synoptic states and conclude that some synoptic patterns can better explain the variability of sea ice than climate indices, such as the Arctic Oscillation, the North Atlantic Oscillation, and the Arctic dipole.

In this study, our focus is on the influence of synoptic states on the surface through their modification of atmospheric and cloud conditions. We study the spatial variability, both vertical and horizontal, and the seasonal variability of cloud responses to synoptic conditions. Our region of interest is the seasonal ice zone of the Beaufort and Chukchi Seas, which has undergone dramatic changes in the last several decades (e.g., Serreze et al. 2007; Stroeve et al. 2012, 2014). The influences of the cloud and atmospheric conditions on sea ice, in particular the sea ice melt onset, are investigated under different synoptic conditions. Satellite observations of clouds and sea ice melt onset and the synoptic classification method are introduced in section 2. The conditions and the atmospheric structure of the identified synoptic states are described in section 3. In section 4, we discuss cloud responses to synoptic conditions in observations and reanalysis. We investigate the role of synoptic conditions on sea ice melt onset in section 5. A discussion and summary are presented in section 6.

2. Data and methods

a. Satellite observations of clouds and sea ice

Obtaining complete and reliable observations of clouds in the Arctic is a challenging problem. Passive remote sensing instruments on satellites have difficulty distinguishing clouds from the snow and ice surfaces under some conditions and significant errors in cloud detection are possible (Y. Liu et al. 2010). Active remote sensors—the Cloud Profiling Radar (CPR) on CloudSat and the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) on CALIPSO in the A-Train constellation—provide detailed vertical distribution of cloud hydrometeors and their properties directly underneath along their ground tracks. However, the lowest levels of CloudSat observations are contaminated by the ground clutter of the radar signal (Marchand et al. 2008). Cloud observations below 500 m and some cloud observations between 500 and 720 m cannot be used (Kay and Gettelman 2009; Mioche et al. 2015). The CALIPSO CALIOP signal is strongly attenuated by liquid droplets and usually cannot detect lower clouds when the visible optical depth of the cloud layer above exceeds 3 (Mace et al. 2009). Therefore, cloud retrievals combining the observations from these two instruments together provide a more complete view of cloud conditions (e.g., Mace et al. 2009; Kay and Gettelman 2009; Mioche et al. 2015). When the CALIOP data are combined with the CPR data, the retrieved radiative fluxes and cloud radiative effects at the surface are improved compared to the radar-only retrievals, due to the inclusion of low-level clouds undetected by the CloudSat CPR (L’Ecuyer et al. 2008; Henderson et al. 2013). The challenge for the combined radar and lidar observations is the low-level liquid clouds below optically thick cloud layers, especially below 720 m. Neither instrument can detect such low-level clouds because of the ground clutter of the CloudSat CPR and the attenuation of the CALIOP lidar signals. It is not uncommon for the optical depth of low-level clouds to exceed the threshold of 3 in the Arctic, according to previous studies of clouds at Barrow, Alaska (e.g., Dong and Mace 2003; Garrett and Zhao 2013), and during the SHEBA campaign over the Beaufort and Chukchi Seas (Matrosov et al. 2003; Shupe et al. 2005; Zuidema et al. 2005). This results in an underestimation of cloud amount below 720 m and also adds to the uncertainty in radiative flux retrievals in these levels and at the surface.

We use the combined CloudSat and CALIPSO cloud retrieval products archived in the CloudSat data processing center (http://www.cloudsat.cira.colostate.edu) to examine the clouds and cloud radiative effects under different synoptic states. For example, the hydrometeor mask is produced using the combined Radar–Lidar Geometrical Profiles (GEOPROF-lidar) product 2B-GEOPROF-lidar (Mace et al. 2009; Mace and Zhang 2014) and the cloud radiative effects are computed using the radiative fluxes and heating rate (FLXHR-lidar) product 2B-FLXHR-lidar (L’Ecuyer et al. 2008; Henderson et al. 2013). The CloudSat on-board battery suffered a malfunction in April 2011 and the satellite left the A-Train constellation for over one year. After its return to the A-Train, the quality of the combined products suffers from the navigational challenges of coordinating measurements from CloudSat and CALIPSO (Mace and Zhang 2014). To avoid the issues due to the changes in the coordination of CloudSat and CALIPSO, we only examine the cloud conditions and cloud radiative effects between 2007 and 2010.

The Arctic Ocean and its marginal seas are cloudy all year round as observed by human, ground-based cloud radar, and spaceborne active and passive remote sensing instruments (e.g., Intrieri et al. 2002; Shupe et al. 2011; Kay and Gettelman 2009; Eastman and Warren 2010; Liu et al. 2012; Mioche et al. 2015). In this study, we use
the combined radar and lidar cloud occurrence (CO), which is the ratio of the number of cloudy observations to the number of all observations, to describe the observed cloudiness in an area of interest. In particular, we describe the spatial variability of the observed cloudiness using the GEOPROF-lidar “shaded cloud occurrence” (SCO), the cloud occurrence computed using the cloud mask that masks a vertical atmospheric profile as cloudy if it is masked cloudy at any level in the vertical in the GEOPROF-lidar cloud mask product. The GEOPROF-lidar SCO of all clouds, low-level clouds (below 3 km), midlevel clouds (3 to 6 km), and high-level clouds (above 6 km) are examined over a grid of 4° longitude by 2° latitude to demonstrate the spatial variability of CO at different levels. This definition of low-level, midlevel, and high-level clouds follows Mace et al. (2009) and corresponds roughly to the pressure-based definitions (low-level clouds below 680 hPa and high-level clouds above 440 hPa) used by the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999).

The footprints of the CloudSat CPR and the CALIPSO CALIOP on the surface trace a web of ground tracks, which are repeated every 16 days with the longitudinal separation between adjacent nodes spaced 1.5° apart at the equator. Because of this spatial and temporal sampling strategy, the sampling uncertainty should be carefully evaluated (van de Poll et al. 2006; Z. Liu et al. 2010). In this study, we used the “moving-block” bootstrap method following Z. Liu et al. (2010) to evaluate the sampling uncertainty and interannual variability of both cloud observations and the atmospheric structure under different synoptic conditions.

Sea ice melt onset is usually related to weather events on a short time scale (e.g., Woods et al. 2013; Mortin et al. 2016). This makes it difficult to use the joint CloudSat and CALIPSO radiative flux retrievals to interpret the cloud radiative effects (CRE) before melt onset events due to the spatial and temporal sampling limitations of the CloudSat CPR and the CALIPSO CALIOP. In addition, previous studies have shown that the timing of transition from positive to negative CRE is sensitive to the choice of surface albedo data, spanning from late April to early July (Intrieri et al. 2002; Schweiger et al. 2008b; Dong et al. 2010; Cox et al. 2016). However, the surface albedo of the joint CloudSat and CALIPSO radiative flux product, 2B-FLXHR-lidar, is prescribed for dry and wet ice seasons (Kay and L’Ecuyer 2013) and therefore does not reflect a natural, gradual progression. As a consequence, the radiative fluxes and CRE from this product are not well suited to interpret short time scale events, especially when the surface albedo also changes abruptly. Instead, we investigate the direct association between the synoptic conditions and sea ice melt onset events.

Passive microwave derived sea ice melt onset data by Markus et al. (2009) are used to study the influence of synoptic activities. Using the brightness temperature at 19 and 37 GHz, Markus et al. (2009) identified the melt onset of snow and ice by the accompanied changes in the surface dielectric properties and emissivity. The melt onset dataset is retrieved using the daily averaged brightness temperature from the Scanning Multichannel Microwave Radiometer and the Special Sensor Microwave Imager and mapped to a grid of 25-km resolution for the period 1979–2014. There are two types of melt onset included in this dataset: the “early melt onset,” the day of the first occurrence of melt, and the “continuous melt onset,” the day after which the sea ice melt persists until the end of summer. Following Mortin et al. (2016), the early melt onset (simply “melt onset” hereinafter) is used because it is more closely related to the atmospheric processes initiating sea ice melt.

b. Classification method

Synoptic weather classification is an investigative technique applied in meteorology, using methods such as the k-means clustering algorithm (e.g., Jakob and Tselioudis 2003; Mülmenstädt et al. 2012; Barton et al. 2012), self-organizing maps (Cassano et al. 2006), and competitive neural networks (Marchand et al. 2009; Evans et al. 2012). The latter two methods are more sophisticated, especially the algorithm by Marchand et al. (2009), which can automatically determine the number of distinctive weather states. However, the resulting number of states is usually large, which makes the interpretation of these states nonintuitive. The k-means clustering algorithm is more straightforward but the number of states has to be prescribed. Previous synoptic classifications of the Arctic region (Mülmenstädt et al. 2012; Barton et al. 2012) have identified four distinct and physically meaningful states using different datasets, variables, and the spatial domain of classification. In this study, we use the k-means clustering algorithm and classify the synoptic conditions in the seasonal ice zone (SIZ) of the Beaufort and Chukchi Seas (the BCSIZ region hereinafter). Following previous studies (Mülmenstädt et al. 2012; Barton et al. 2012), four states are selected as a priori to allow for a meaningful separation of states, with both mathematically and physically different dominant characteristics, while keeping the number to a level that allows for a convenient interpretation of the states. The BCSIZ domain is defined as the region bounded by 170°W, 130°W, 70°N, and 80°N (Fig. 1).

As input to the k-means clustering algorithm, we use thermodynamical and dynamical variables at multiple
vertical levels from the ERA-Interim reanalysis (Dee et al. 2011) by the European Centre for Medium-Range Weather Forecasts (ECMWF), because of its better performance in the Arctic compared to other reanalyses products (e.g., Cox et al. 2012; Zib et al. 2012; Cullather and Bosilovich 2012; Lindsay et al. 2014). We use 6-hourly pressure level and surface reanalysis products for the 15-yr period 2000–14 with a horizontal resolution of 0.7° in both latitude and longitude. The variables used for classification include surface pressure, with temperature, specific humidity, geopotential height, and horizontal winds from six pressure levels: 1000, 950, 900, 850, 700, and 500 hPa. Using multiple vertical levels in the lower and middle troposphere in the BCSIZ region, the spatial pattern and the vertical structure of the dynamical and thermodynamical fields are incorporated in the classification processes and reflected in the final synoptic states.

The k-means clustering algorithm iteratively clusters all 21,916 instances of the 6-hourly data from 2000 to 2014 into the four prescribed states. For each 6-hourly data instance, every variable at every level in every grid box is considered a dimension of the data instance vector. First of all, four instances of the 6-hourly data are selected randomly as the initial centroid vector of the four states. All remaining instances are classified to the state that has the smallest Euclidean distance between the instance and the initial centroid. The centroids of the resulting four clusters are used as the updated centroids for the next iteration. This process is iterated until the four states and their centroids converge and do not change with iteration. All the variables are normalized before the Euclidean distance is calculated. The anomaly fields are constructed by removing the BCSIZ domain mean annual cycle: the BCSIZ domain mean

FIG. 1. Map of the mean 700-hPa level temperatures (colors, °C), winds (vectors), and geopotential height (contours) of the four synoptic states for 2007–10. The contours are shown in gray with high values in black and low values in white. The BCSIZ region is outlined by the red lines in the upper-left panel.
values at the corresponding levels and in the cor-
responding month of year. In this way, both the horizontal and the vertical features are preserved in the anomaly fields and they will be the key patterns recognized by the k-means clustering algorithm. Then, the anomaly fields at each grid point are normalized by their root-mean-square (RMS) during the corresponding month of the year throughout the total period of classification. The normalization ensures the same magnitude of variability of different variables at every grid point and time stamp, so that their weightings in the computed Euclidean distance are not biased. The resulting states are exam-
ined for their separation from each other. Mathemati-
cally, the mean Euclidean distance of the members in a given state from the centroids of the other states should be farther away than from their own state centroid, by at least one standard deviation of the Euclidean distance from their state centroid. The uncertainty of the state mean fields and the statistical significance of the differences between states are evaluated using the “moving-
block” bootstrap resampling method (Wilks 1997; Z. Liu et al. 2010), with a block length of 2 days, to take into account the temporal autocorrelation of synoptic events. The block length of 2 days corresponds to the mean duration of synoptic events continuously classified as the same state. The classification of the 15 yr of data from 2000 to 2014 converges after 82 iterations. A second set of classifications is implemented using subsets of the 15-yr dataset: 2000–06, 2007–11, and 2012–14. All classifications produce four distinctive states and the mean states of the second set of classifications correspond well with the mean states of the 15-yr classification. For both the 15-yr and 5-yr 2007–11 classifications, the sensitivity to the choice of initial centroids is examined. Using differ-
ent initial centroids, both randomly chosen centroids and the classified mean states from Müllerstädt et al. (2012), the classifications still converge to the same results as the original classifications, demonstrating robustness of the classification and that the resulting states capture the persistent synoptic features in the BCSIZ region. In the following analysis and discussion, the 15-yr classification of ERA-Interim data is used. However, the focus is on the period 2007–10, to be consistent with the availability of the CloudSat and CALIPSO combined radar and lidar cloud observations.

3. Synoptic conditions of the identified states

A map of 700-hPa level temperature, winds, and geopotential height of the four synoptic states for the period 2007–10 shows both the BCSIZ domain and its ambient area (Fig. 1). The first state (S01) is associated with a high pressure over the western part of the BCSIZ domain and northerly winds to the east, where there is strong baroclinicity and cold advection from the central Arctic. The baroclinicity is shown by the gradient of geopotential height and temperature, and the crossing angle between the geopotential height contours and temperature contours (Fig. 1). The second state (S02) is associated with low pressure over the northeastern part of the BCSIZ domain and is dominated by westerly and northwesterly winds. Compared to S01, S02 has much weaker baroclinicity and weaker cold advection from the Siberian side of the Arctic Ocean. The third state (S03) is associated with a high pressure system to the southeast far into the North America continent and the low pressure system is to the northwest of the BCSIZ region. In the BCSIZ domain, S03 has intermediate baroclinicity compared to S01 and S02, with a large crossing angle between the temperature and geopotential contours, but not as large as S01. The last state (S04) is characterized by an evident high pressure center over the Beaufort Sea, which results in very strong warm advection to the west and some cold advection to the east (on the eastern edge of the BCSIZ domain). Similar to S01, S04 is also a state with strong baroclinicity. In addition to the stronger baro-
clinicity compared to S03, the warmest air mass in S04 is over Alaska and very close to the strongest southerly winds, while the warmest air mass in S03 resides deep inland. The combined effect is a much stronger warm advection and warmer atmosphere in S04 than in S03.

These four synoptic states are qualitatively consistent with the states identified by Müllerstädt et al. (2012), who report a high pressure cold advection state, a low pressure cold advection state, and a warm advection state in the BCSIZ region. For these three states, the 700-hPa synoptic maps of their mean states (not shown) are similar to the conditions shown in Fig. 1, but the exact location and the relative strength of the high pressure and low pressure centers differ. Müllerstädt et al. (2012) also report a state that resembles a combination of S01 and S03 of this study. The consistency of the states identified here with those of Müllerstädt et al. (2012) suggests the physical robustness of these states. The differences may be due to their use of a different reanalysis product from 2000 to 2010 and using only surface variables at Barrow, Alaska.

The vertical profiles of domain mean temperature, relative humidity, specific humidity, and horizontal wind speed (Fig. 2) show that S02 is the coldest state and the least stratified at low levels. Together with the highest mean relative humidity, S02 provides favorable conditions for the formation and maintenance of low-level clouds. State S04 is not only the warmest state but also most strongly stratified at the lower levels, with a 4.0-K
mean inversion at 925 hPa. With much higher temperature, the relative humidity of S04 is lowest of all four states despite its relatively high specific humidity. This is likely due to the continental origin of the air mass in the BCSIZ domain and the downslope warming and drying over the Brooks Range. Both S03 and S04 have much stronger mean winds below 900 hPa and more developed low-level jets (LLJs) than the other two states, which is likely related to their stronger baroclinicity (Stull 1988).

The lower-tropospheric static stability (LTS) is important for the cloudiness for both the Arctic boundary layer (e.g., Schweiger et al. 2008a; Kay and Gettelman 2009) and the marine boundary layer of lower latitudes (Klein and Hartmann 1993). In this study we define the LTS as the difference in potential temperature between 850 hPa and the surface. In the BCSIZ domain, there is a clear dependence of the mean LTS on the synoptic regimes (Fig. 3). The seasonal variability of the domain mean LTS is about 10 K for all four states. Despite the large seasonal variability, the LTS of S04 is greatest throughout the year, due to the strong warm advection in S04. Similarly, with moderate warm advection, the LTS of S03 is less and the LTS of S02 is the least with cold advection. Despite the strong cold advection in S01, the LTS of S01 is even greater than S03. For all four synoptic states, the LTS is greatest in winter and decreases rapidly in early spring, because when the sun comes above the horizon in spring, the extremely cold surface warms more rapidly than the air at 850 hPa. From late spring to midsummer, the LTS increases again, probably because the surface temperature is bounded by the melting point of sea ice and the air temperature at 850 hPa catches up. Compared to S01 and S02, the earlier increase of LTS in S03 and S04 from May to June is likely due to the advection of the warm air mass from lower latitudes. As the sea ice starts to melt and the ice edge retreats in the BCSIZ domain in summer, the LTS decreases again because the surface temperature over ice free areas is no longer pegged to the melting point.

Of the four synoptic states, the S02 state occurs much more frequently in winter than in summer, while S04 favors late summer and early autumn (Fig. 4). The seasonal preference of the other two states is weaker, with S01 occurring more frequently in the autumn, and S03 more frequently in later spring and early summer. Although the seasonal preference of the four states

![FIG. 2. The mean vertical profiles of (left)-(right) temperature, relative humidity, specific humidity, and wind speed of the four synoptic states in the BCSIZ domain for 2007–10: S01 (blue), S02 (green), S03 (red), and S04 (cyan). The color shadings indicate the 95% confidence interval.](image1)

![FIG. 3. The mean annual cycle of the ERA-Interim LTS of the four synoptic states for 2007–10: S01 (blue), S02 (green), S03 (red), and S04 (cyan). The color shadings indicate the 95% confidence interval.](image2)
introduces variabilities in the mean atmospheric profiles of the four states in the BCSIZ region (not shown), the spatial patterns and the vertical structure (Figs. 1 and 2) of the atmosphere of the four states are robust. For example, S04 is the warmest state with the highest LTS in all seasons and S02 is the coldest state with the lowest LTS in all seasons.

4. Cloud conditions

a. Cloud conditions in the BCSIZ

The spatial distributions of the GEOPROF-lidar SCO and the ERA-Interim cloud cover at different levels show that the BCSIZ region is cloudy in general, with the mean SCO over 70% (Fig. 5). Although cloudiness in the BCSIZ is dominated by low-level clouds, midlevel and high-level clouds are common as well. The SCO of midlevel and high-level clouds is as high as half of low-level SCO. Excluding clouds above 3 km, the SCO in the BCSIZ region is reduced by over 10%. There are more clouds to the west over the Chukchi Sea, especially close to the Bering Strait, and to the south along the coast. The highest high-level SCO are found in the southernmost grid boxes along the coast and the lowest SCO over the northeast corner of the BCSIZ region, which is associated with the proximity to moisture transport from lower latitudes. The ERA-Interim total cloud cover shows more clouds than the GEOPROF-lidar observations, which is attributable mostly to the overestimation
of low-level clouds. There are more low-level clouds in the northwestern BCSIZ domain in ERA-Interim and the least cloud cover is to the south along the coast. This clearing at the coast is absent from observations. The midlevel cloud fraction in ERA-Interim bears resemblance to the spatial distribution of low-level clouds of both ERA-Interim and the observations. The differences in midlevel clouds may be partly attributed to the mismatch in the partition of vertical levels and the poor sampling of GEOPROF-lidar. There are not enough high-level clouds in ERA-Interim although the spatial distribution of high-level clouds does agree with the GEOPROF-lidar observations.

The annual cycle of the SCO of all clouds, low-level clouds, midlevel clouds, and high-level clouds in the BCSIZ region shows the all-cloud SCO maximum occurring in October and a secondary maximum in late spring, which is followed by a sharp reduction in SCO in early summer (Fig. 6). The presence of two maxima in Arctic cloudiness was documented in previous studies using observations from ground-based upward-looking cloud radars at several surface sites (e.g., Shupe et al. 2011) as well as by the joint CloudSat and CALIPSO observations over the entire Arctic (e.g., Liu et al. 2012; Mioche et al. 2015). This variability of all-cloud SCO is mostly due to the variability of low-level clouds. The midlevel clouds and high-level clouds have much weaker month-to-month variability and the observed SCO maximum occurs in August rather than October as for low-level clouds and all clouds.

Compared to the observed SCO, the ERA-Interim all-cloud and low-level cloud fraction has a much weaker annual cycle. Although the maximum cloud cover in October is reproduced, the late-spring peak is not apparent. Throughout the year, the ERA-Interim has too much cloud cover, especially low-level clouds, with the highest bias in winter and early summer. The midlevel and high-level cloud cover in ERA-Interim is smaller than the observed SCO. Because of the ground clutter of the cloud radar and the attenuation of lidar signal under optically thick clouds, some clouds are not detected in GEOPROF-lidar under 720 m. These undetected clouds have little effect on the calculation of the all-cloud SCO because, in these cases, the atmospheric column is still marked cloudy due to the presence of the optically thick clouds above these undetected clouds. Low-level SCO is more likely to be affected by these undetected clouds, but the resulting underestimation of cloudiness is much smaller than the discrepancy with the ERA-Interim cloud amounts. Positive biases in low-level and total clouds
in the ERA-Interim were also reported in previous studies (e.g., Zib et al. 2012; Lindsay et al. 2014; Klaus et al. 2016; Liu and Key 2016). The large overestimation of cloud fraction in ERA-Interim during winter and early spring is likely due to the difficulty of the ECMWF model to capture the physics of the strongly stratified boundary layer as well as the treatment of mixed-phase cloud processes (Zhao and Wang 2010; Forbes and Ahlgrimm 2014; Klaus et al. 2016).

### b. Cloud conditions of different synoptic states

Figure 7 shows vertical profiles of the observed mean CO and the ERA-Interim mean cloud fraction of the four synoptic states in the BCSIZ region. S02 and S04 reflect the most distinct states with respect to cloudiness and bracket S01 and S03. S02 has the highest CO with 48% at about 1 km and its CO decreases significantly with height to 17% at 6 km. S04 has more high-level clouds than the two cold advection states, S01 and S02, and even more than S03 above 8 km. S04 has the least low-level clouds, which is consistent with its driest lower atmosphere. For S01 and S03, CO decreases slightly with height from 2 km to 6 km and at a much faster rate above 6 km. With moist and warm air, the warm advection state S03 has CO above 30% in midlevels while the cold advection state S01 has CO values of less than 20%. Except for the strong warm advection state S04, all the other states have the highest CO at levels around 1 km.

The ERA-Interim reproduces these features of the vertical profiles of cloud fraction for the four synoptic states as well as their differences from each other. The ERA-interim cloud fraction is less than the observed CO by about 10% from 1 km to 8 km. This is consistent with the underestimation of midlevel and high-level shaded cloud fraction by ERA-Interim (Fig. 6). The overestimation of low-level clouds (Fig. 6) is mostly due to the overestimation of clouds below 1 km. The low-level cloud fraction peaks are lower vertically, below 500 m for all four states in the ERA-Interim, while the peaks are around 1 km in GEOPROF-lidar, except for S04. Because of the limitations of the CloudSat and CALIPSO sensors when optically thick clouds exist below 720 m, as described in section 2a, the discrepancies between ERA-Interim and GEOPROF-lidar in these levels can be partly attributed to the missing clouds in GEOPROF-lidar.

Synoptic conditions also affect the horizontal distribution of clouds in the BCSIZ domain. Using the mean SCO maps as a reference (Fig. 5), we examine the differences of the four synoptic states from the mean SCO.
The differences from the mean SCO or the “anomaly” for all clouds and for low-level, midlevel, and high-level clouds are shown in Fig. 8. Overall, S01 has more clouds to the east and along the coast to the south. A possible reason for the positive anomaly of the low-level clouds along the coast is the moisture brought in by the strong onshore flow in S01 (Clark and Walsh 2010). S02 has more clouds than the mean, with the largest positive anomaly along the coast and to the east of the BCSIZ domain. The positive low-level cloud anomaly is evident everywhere in the BCSIZ domain, with the greatest cloud amounts occurring to the east and to the south along the coast. Because of the lack of high-level clouds in S02 it is less cloudy than S03 when clouds of all levels are included. S03 is the cloudiest state. Despite the large positive anomaly in high-level clouds, S04 is the state with the fewest low-level and midlevel clouds of all states. Although the horizontal distribution of the all-cloud SCO is dominated by low-level clouds, high-level clouds are still an important element of the cloud cover of the BCSIZ region. It is noteworthy that the cloud cover anomaly of ERA-Interim has a similar spatial pattern as the observed SCO anomaly for all states at all levels (not shown), despite the differences in the mean cloudiness between them, especially at low levels. This suggests that the synoptic control of cloud cover is captured by the ERA-Interim.

The annual cycles of GEOPROF-lidar low-level SCO and the ERA-Interim low-level cloud fraction for all states are shown in Fig. 9. The annual cycles of S01, S03,
and S04 are similar to the mean annual cycle for all states (Fig. 6), with SCO maxima in late spring and early autumn. S02 has a high SCO (more than 80%) period from May to October, and a low SCO (less than 70%) period from December to April. The SCO peaks in May and September are not as obvious as for the other states. The seasonal variability of the ERA-Interim low-level cloud fraction for all four states is too weak compared to observations. The late spring and early autumn SCO maxima for S01, S03, and S04 are not well reproduced. The winter–summer SCO contrast of S02 is not captured at all. Overall, ERA-Interim has too much cloud cover under all synoptic conditions and therefore fails to fully reproduce the observed annual cycle.

c. Synoptic states and physical mechanisms controlling cloud variability

The mean ERA-Interim LTS in the BCSIZ region is shown in Fig. 10. The LTS is lower along the western boundary of the BCSIZ, especially at the southwestern corner, close to the Bering Strait. To the east, the LTS is higher by almost 5 K. This spatial pattern of LTS matches the spatial pattern of the observed low-level SCO (Fig. 5), with more clouds at locations with lower LTS and fewer clouds at locations with higher LTS. The correspondence between the observed cloudiness and LTS is also shown in their seasonal variability. The LTS minima in late spring and early autumn (Fig. 3) correspond to the observed low-level SCO maxima, and the peaks of LTS in winter and early summer correspond to the observed low-cloud SCO minima.

The low-level SCO anomalies of the four synoptic states are closely related to their LTS anomalies relative to the mean LTS (Fig. 10). S01 has fewer low-level
clouds than the mean to the northwest of the BCSIZ domain and more clouds over the area along the eastern boundary and along the coast to the south of the BCSIZ domain. The spatial contrast of the positive and negative anomaly in low-level clouds matches the negative and positive LTS anomaly of S01 (Fig. 11). This spatial correspondence between the low-level cloud anomaly and the LTS anomaly is also found for other states. Relative to the mean low-level SCO, S03 has more clouds to the east of the BCSIZ domain and fewer clouds to the west, which corresponds to the LTS anomaly pattern (Fig. 11). Throughout the BCSIZ domain, S02 has more low-level clouds than the mean and S04 has less low-level clouds than the mean, which is consistent with the negative LTS anomaly of S02 and the positive LTS anomaly of S04.

LTS and the observed cloudiness are inversely correlated in terms of both the spatial variability and the seasonal variability for all four synoptic states. The cloud–LTS correlation is tied to vertical mixing and entrainment both in the Arctic and over subtropical oceans, but the effect on cloudiness is opposite. A larger LTS, especially with a larger cloud-top temperature inversion, means weaker mixing between the free troposphere and the cloud-topped boundary layer. Over the subtropical ocean, a weaker mixing between the moist air in the boundary layer and dry air above helps keep the boundary layer moist and maintains a larger cloud fraction (Klein and Hartmann 1993; Wood and Bretherton 2006). In the Arctic, low-level clouds are usually decoupled from the moisture source at the surface (Shupe et al. 2013) and the specific humidity inversion, which is frequently observed at the top of the boundary layer, is an important source of moisture for the maintenance of the Arctic stratocumulus cloud, especially when a temperature inversion is also present (Devasthale et al. 2011; Solomon et al. 2011, 2014). A larger LTS and weaker mixing therefore reduce the entrainment of moisture from above the clouds and can lead to a decrease in cloud fraction. For cases where the subcloud mixed layer is coupled to the surface, larger LTS can inhibit the supply of moisture from the surface. This mechanism provides an explanation for the negative correlation between the LTS and the low-level cloud fraction.

Although the LTS is regulated by synoptic conditions and links to low-level cloudiness by controlling local moisture supply, synoptic conditions also directly affect cloudiness. For example, the downslope air across the Brooks Range in S04 is very warm and leads to larger LTS in BCSIZ. At the same time, the relative humidity of the downslope air is low and not favorable for cloud formation and maintenance. The relationship between LTS and low-level clouds in the Arctic is complicated by the feedback between low-level clouds and surface temperature. During winter, the cloud longwave radiative heating can quickly warm the underlying surface and decreases LTS. In the Arctic, the LTS also depends on the temperature of the free troposphere, which varies significantly due to the temperature advection under different synoptic conditions. In addition to the study of relevant cloud processes such as mixed-phased cloud processes (e.g., Solomon et al. 2011; Ovchinnikov et al. 2014; Sulia et al. 2014), the role of different synoptic conditions should also be considered to further understand the mechanisms controlling the low-level cloudiness in the Arctic and how Arctic clouds respond to the projected sea ice decline in summer and autumn (Schweiger et al. 2008a; Kay and Gettelman 2009).
Upper-level cloudiness is controlled synoptically by different processes. High-level SCO anomalies of the four states are related to the upper-level moisture and the vertical motion of the upper level atmosphere in the presence of upper-level ridges and troughs. Here we use the 500-hPa vertical pressure velocity anomaly (positive values for downward motion and negative values for upward motion) of the four synoptic states (Fig. 11) to characterize the vertical motion in the upper levels of atmosphere. S01 has negative high-level cloud anomaly, associated with the sinking motion of the upper levels in the BCSIZ domain ahead of the upper-level ridge to the west. S02 has upper-level sinking motion to the west of the BCSIZ domain behind the upper-level trough and rising motion to the east ahead of the trough. However, because of the dry upper levels of S02 (Fig. 2), the high-level SCO S02 has a large negative anomaly except in the southeastern corner where the upward motion is strongest. The largest SCO negative anomaly is over 15% to the west of the BCSIZ domain. For S03, there is strong upper-level upward motion in the entire BCSIZ domain and the largest vertical velocity is around the center of the BCSIZ domain, which is consistent with the large positive anomaly of high-level SCO. With the upper-level ridge in the middle of the BCSIZ domain in S04, the upper-level air is rising to the west and sinking to the east. Because of the moist anomaly of S04 in upper level, there is a large positive high-level SCO anomaly in most of the BCSIZ domain except in the southeastern corner where the downward motion is strongest.

5. The effect of synoptic state on sea ice melt onset

Given the clear link between synoptic states and the structure of the upper atmosphere and cloud conditions, is the occurrence of synoptic states connected to sea ice variability? Temperature, moisture, and clouds differ significantly under the four synoptic states. Consequently, the interactions between the atmosphere and the underlying surface, in particular, the Arctic sea ice, differ under different synoptic conditions, which affect clear-sky radiative heating, cloud radiative effects, and turbulent fluxes at the surface. Woods et al. (2013) report that intense moisture intrusions into the Arctic from lower latitudes are important for the total poleward moisture transport. Their composites of these moisture intrusion events show a close association with large-scale circulation patterns in the Arctic, such as the anticyclonic blocking high. The radiative heating associated with the moisture intrusion events is connected to the change in sea ice concentration (Park et al. 2015a) and the timing of the melt onset (Mortin et al. 2016). Here we explore the relationship between synoptic conditions and melt onset in the BCSIZ.

Which synoptic conditions drive melt onset? Figure 12 shows the frequency of occurrence of each synoptic state in the 5-day period before the melt onset for the period from 2000 to 2014. In most regions of the BCSIZ, about 50% of the time in the 5 days before the melt onset, the BCSIZ is under state S04. State S03 is the second most likely state to precede the melt onset in the BCSIZ, despite the fact that S03 and S04 are much less likely to occur than S01 and S02 during the melting season from April to June (not shown). S04 is the warmest state with the highest specific humidity at all levels and hence the highest precipitable water. S03 is the second highest in term of temperature and precipitable water. This is consistent with Mortin et al. (2016), who report positive anomalies of temperature and precipitable water before the melt onset occurs.

How does the timing of melt onsets relate to synoptic conditions? Do some states lead to earlier melt onsets than others? We assign a melt onset event to a synoptic state if it is the most frequently occurring state in the 5-day period before the melt onset. The mean melt onset time of the four synoptic states from 2000 to 2014 (Fig. 13) shows that S04 is associated with the earliest melt onsets, which occur in early to mid-May in most of the BCSIZ domain. S03 is connected to later melt onsets compared to S04, but still earlier than the other two states. This result agrees with the findings of Mortin et al. (2016) that higher temperature and precipitable water are associated with earlier melt onsets. Both the
higher temperature and the higher precipitable water values of S04 are favorable for melt onset because they lead to higher downward LW fluxes and turbulent fluxes at the surface.

Here, higher precipitable water, or the moisture associated with early melt onset, does not necessarily mean higher relative humidity. The high precipitable water in S04 is due to the large specific humidity associated with high temperatures. As a result, S04 has lower relative humidity compared to other states and less low-level cloudiness. The combination of warm and moist air with relatively fewer low-level clouds has the highest probability of yielding a surface energy balance conducive to melt onset. This seems to conflict with prior results of Kapsch et al. (2013) and Mortin et al. (2016) that associate the early sea ice melt onset with positive cloud anomalies as a result of poleward atmospheric transport of heat and moisture. Indeed, the warm, moist, and cloudy conditions of S03 are favorable for early melt onset in BCSIZ compared to the cold advection states S01 and S02, even if S02 has more low-level clouds. Even though S04 has fewer low-level clouds than S03, downwelling longwave emissions exceed those from S03 because emissions at higher temperatures and with more column integrated water vapor compensate for the cloud deficit. Solar heating at the surface increases with more clear sky. In addition, turbulent fluxes toward the surface also increase under a warmer and moister atmosphere. The effects of the higher cloud emitting temperature, more solar heating, and larger turbulent fluxes prevail over the radiative longwave effects of smaller cloud cover and make S04 more favorable than S03 for early melt onset in the BCSIZ. Regional variability is another possible explanation for the disagreement with previous studies. S04 in the BCSIZ region may be special because of the combination of the southerly flow associated with the Beaufort high and the downslope warming of the already warm continental air mass from Alaska when passing over the Brooks Range. Both Kapsch et al. (2013) and Mortin et al. (2016) use cloud and radiative fluxes from ERA-Interim, which has the best representation of the observed clouds and radiation in the Arctic (e.g., Cox et al. 2012; Zib et al. 2012; Lindsay et al. 2014). ERA-Interim, however, still has difficulties reproducing the observed seasonal variability of SCO and the distinctions between different synoptic conditions. For example, S04 has about the same low-level cloud fraction as S03 in ERA-Interim in May, but in observations S04 has about 15% fewer low-level clouds (Fig. 9). Note that extreme poleward moisture transport or moisture intrusion events were usually narrow in spatial scale and these events were frequently accompanied by a blocking high pressure system (Doyle et al. 2011; Woods et al. 2013). In S04, the high pressure system over the BCSIZ and high temperatures are favorable for the moisture intrusion events.

6. Summary and discussion

The connection between the synoptic weather and the cloudiness of the Arctic has been explored by recent studies (Cassano et al. 2006; Müllmenstädt et al. 2012; Barton et al. 2012) and the classification of synoptic states is generated using either surface variables or thermodynamic and dynamic variables for some specific layer or level. In this study, we use the k-means clustering algorithm and 6-hourly thermodynamic and dynamic variables in the lower atmosphere, from the surface up to 500 hPa. In this way, important vertical structures of the Arctic boundary layer, such as the temperature inversion, the specific humidity inversion, and the LLJ, are preserved. Four distinct synoptic states are identified. State S01 is dominated by a high pressure center to the west of the BCSIZ and strong cold advection. State S02 is dominated by a low pressure center to the northeast of the BCSIZ and weaker cold advection compared to S01. State S03 is dominated by a moderate warm advection between a trough to the northwest and a ridge to the southeast of the BCSIZ. State S04 is dominated by a high pressure center in the BCSIZ and strong warm advection. Corresponding to the synoptic conditions, the vertical profiles of
temperature, moisture, and winds of each state differ distinctly. Using the synoptic classifications and the joint CloudSat and CALIPSO observations of the vertical structure of cloud properties, we study the cloud conditions in the BCSIZ under the four synoptic conditions. In general, there are more clouds to the west and south of the BCSIZ domain, which is dominated by low-level clouds. The seasonal variability of the SCO in the BCSIZ is also dominated by low-level clouds, with SCO maxima in May and October. The two SCO maxima were observed in previous studies using both ground-based and satellite-borne active remote sensing instruments in the Arctic (e.g., Intrieri et al. 2002; Shupe et al. 2011; Liu et al. 2012). The fact that these two peaks exist in all states suggests that the seasonal variability of local processes is the reason for these two maxima.

The four states emphasize different perspectives of the synoptic conditions from the traditional concepts of two preferred states of surface and atmospheric conditions (e.g., Stramler et al. 2011; Morrison et al. 2012). In the two-state perspective, the warm, moist, and opaque cloudy state and the cold, dry, and radiatively clear state describe the local signatures of atmospheric conditions, clouds, and cloud radiative heating at the surface as a result of the passing synoptic disturbances. The four synoptic states identified in this study focus on the dominant spatial patterns of these synoptic disturbances, the influence of these spatial patterns on clouds and sea ice, and their seasonal variability. The bimodal structures of the histograms of the surface net and downwelling longwave radiative fluxes for all grid points in the BCSIZ are found in all four synoptic states (not shown). The atmospheric and cloud conditions associated with the two modes are present in all four states. The two modes correspond to the areas under the influence of high versus low surface pressure in the BCSIZ region.

The variability of the SCO anomalies of the four synoptic states relative to the mean SCO is mostly determined by low-level clouds. Both the seasonal and spatial variabilities of the observed low-level SCO correspond well with the LTS variability of the four synoptic states. LTS is regulated by synoptic conditions, which also affect cloudiness directly through the poleward transport and energy and moisture. The correlation between the LTS and low-level cloudiness is likely established through the synoptic modulation and the interactions between LTS and cloud, such as the effects of the LTS on the moisture entrainment in the presence of a moisture inversion and the cloud radiative heating on the surface temperature.

The spatial variability of high-level clouds is similar to the high-level relative humidity and the 500-hPa vertical pressure velocity. LTS and the 500-hPa vertical pressure velocity are the two variables used by Barton et al. (2012) to perform their k-means classification, although they chose these two variables because this combination produced the largest separation in the cloud statistics of their classified synoptic states. Considering the importance of the 500-hPa vertical velocity for high-level clouds and the close correlation of LTS with the low-level cloud, it is not surprising that a classification using these two variables produced the most distinct cloud conditions in Barton et al. (2012).

Consistent with previous studies, we find the ERA-Interim overestimates the cloud fraction, particularly the low-level cloud fraction in winter and early spring (Zib et al. 2012; Lindsay et al. 2014; Klaus et al. 2016; Liu and Key 2016). As a result, the seasonal cycle of cloud fraction is much weaker than in observations, regardless of the synoptic conditions. However, ERA-Interim reproduces well the vertical distribution of cloud fraction and the horizontal distribution of cloud fraction anomaly under different synoptic states. This suggests that the synoptic conditions provide a tight constraint on where the clouds can form and develop spatially in the atmosphere through the thermodynamic and dynamic structure of each synoptic state, which is relatively well reproduced by ERA-Interim. However, the life cycle of clouds, how they form and develop, also depends on the performance of the physical parameterizations in the ECMWF model, such as the surface roughness, the boundary layer turbulent mixing, and the mixed-phased cloud microphysics in the highly stratified Arctic winter boundary layer (e.g., Holtslag et al. 2013; Morrison et al. 2012; Ovchinnikov et al. 2014). Further study of these physical processes will help improve the representation of clouds and the surface energy balance in the ECMWF model and other numerical models. This is critical because the community is working toward removing the cloud biases and achieving a better reproduction of the observed annual cycle of cloudiness in this region (e.g., Beesley and Moritz 1999; Vavrus and Waliser 2008; Zhao and Wang 2010; Forbes and Ahlgrimm 2014). The synoptic classification presented in this study can serve as an effective framework to evaluate the performance of global and regional models in their representation of different synoptic states in terms of their dynamic and thermodynamic conditions, and investigate the simulated clouds and cloud processes under these synoptic conditions (e.g., Marchand et al. 2009; Evans et al. 2012; Muhlbauer et al. 2014; Evans et al. 2014).

Is variability in the synoptic states linked to the variability in sea ice? Synoptic states with higher temperature and precipitable water, even though they occur less often during the melt season, occur more frequently...
prior to sea ice melt onset events, and are especially associated with earlier melt onset. This is consistent with the findings of Mortin et al. (2016). However, in the BCSIZ, the warmest yet least cloudy state (S04) is most closely connected to earlier melt onsets. Because of the high sensitivity of cloud radiative fluxes to the cloud temperature, especially at higher temperatures, the combination of the high temperature and large precipitable water of S04 helps compensate for the relative lack of low-level clouds compared to other states. In addition, the presence of a high pressure system over the BCSIZ in S04 is favorable for intense filamentary moisture intrusion events (Woods et al. 2013). These events can also contribute to early sea ice melt onsets, although on a much smaller spatial scale (Mortin et al. 2016). The strong connections between the synoptic weather events and the sea ice melt onset shown in this study point the way to further work. How is the melt onset timing and the northward propagation affected by the mean state (e.g., temperature, humidity, and cloudiness, etc.) of each synoptic type? Do we expect a change of synoptic state occurrence associated with changes in the large-scale circulation in response to climate change? How does the timing of melt onset affect the long-term changes and seasonal evolution (Petty et al. 2017) of the sea ice cover?

The connection between synoptic conditions and sea ice melt onset is only one example of the importance of synoptic conditions on sea ice in the BCSIZ region. Synoptic conditions have an important influence on sea ice in other seasons as well. A recent study by Persson et al. (2017) examined two events of poleward heat and moisture transport during the SHEBA campaign. They report that the net surface heating warmed the surface and penetrated through the sea ice and slowed sea ice bottom growth. Further study of the role of synoptic conditions on cloud and sea ice in different seasons will help to advance our knowledge of the physical processes controlling the seasonal variability of sea ice and may hold the keys to advance simulations of sea ice in global climate models (e.g., Park et al. 2015b; Cox et al. 2016; Letterly et al. 2016).

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