Interannual Variations of Arctic Cloud Types in Relation to Sea Ice

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ABSTRACT

Sea ice extent and thickness may be affected by cloud changes, and sea ice changes may in turn impart changes to cloud cover. Different types of clouds have different effects on sea ice. Visual cloud reports from land and ocean regions of the Arctic are analyzed here for interannual variations of total cloud cover and nine cloud types, and their relation to sea ice.

Over the high Arctic, cloud cover shows a distinct seasonal cycle dominated by low stratiform clouds, which are much more common in summer than winter. Interannual variations of cloud amounts over the Arctic Ocean show significant correlations with surface air temperature, total sea ice extent, and the Arctic Oscillation. Low ice extent in September is generally preceded by a summer with decreased middle and precipitating clouds. Following a low-ice September there is enhanced low cloud cover in autumn. Total cloud cover appears to be greater throughout the year during low-ice years.

Multidecadal trends from surface observations over the Arctic Ocean show increasing cloud cover, which may promote ice loss by longwave radiative forcing. Trends are positive in all seasons, but are most significant during spring and autumn, when cloud cover is positively correlated with surface air temperature. The coverage of summertime precipitating clouds has been decreasing over the Arctic Ocean, which may promote ice loss.

1. Introduction

Arctic climate has changed dramatically in the past two decades. End-of-summer sea ice extent has declined and reached surprisingly small values in 2007 and 2008 (Stroeve et al. 2008; Comiso et al. 2008). Shrinking ice cover has been accompanied by an increase in surface air temperature (SAT) of almost 0.5°C decade$^{-1}$ from 1979 through 2003, as observed by the International Arctic Buoy Programme (Rigor et al. 2000).

Clouds are thought to have an important role in the Arctic climate system, though their role is not completely understood, and climate modeling studies have not been well substantiated by observations. Vavrus (2004) modeled Arctic greenhouse warming, including cloud feedbacks, concluding that $\sim$40% of the ultimate Arctic greenhouse warming was due to cloud changes resulting from the warming. Beesley (2000) modeled the seasonal cycle of ice thickness, finding that an increase of low clouds would lead to thicker ice, and an increase of high clouds would lead to thinner ice. Francis and Hunter (2006) analyzed infrared sounding data from satellites, and found a positive correlation between ice retreat and downward longwave cloud radiative effect (CRE), suggesting that infrared radiation emitted toward the surface by clouds can cause sea ice melt. [CRE is the difference in radiation flux between (a) the average of all sky conditions and (b) clear sky.] Francis and Hunter also stated that cloud phase may be related to the anomalies of downward longwave radiation, with water clouds emitting more longwave radiation than ice clouds because they are optically thicker, and therefore have higher emissivity. Shupe and Intrieri (2004) agree, stating that cloud phase, temperature, and height have a strong impact on CRE. Their research, which was part of the “Surface Heat Budget of the Arctic” (“SHEBA”) program and employed radar, lidar, pyranometer, radiometer, and radiosonde data from 1997 and 1998, indicates that for longwave radiation, the majority of radiatively significant cloud scenes have bases lower than 4.3 km and cloud temperatures greater than $-31^\circ$C.

Cloud radiative effect over the Arctic likely varies seasonally. Most studies agree that clouds have a warming effect during all seasons except summer. The warming is due to emission of longwave radiation by clouds, while
cooling in summer is due to scattering of incoming short-wave radiation. Longwave warming dominates throughout the dark months in the Arctic, while shortwave cooling can only take place during summer when the sun is high and the snow has melted, lowering the surface albedo. The exact timing and duration of the negative CRE is not agreed upon. Using SHEBA data, Intrieri et al. (2002) found only a few weeks during midsummer when CRE is negative. Using a 1D coupled model, Curry and Ebert (1992) also determined that CRE over the Arctic is positive, except for 2 weeks during midsummer. Walsh and Chapman (1998) used radiation measurements taken on drifting Russian weather stations as well as National Centers for Environmental Prediction (NCEP) and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data and inferred negative CRE from May through July. The net CRE was positive from September through March. Using the second Global Environmental and Ecological Simulation of Interactive Systems (GENESIS2) general circulation model (GCM), which claimed to compute Arctic cloudiness particularly well, Vavrus (2004) showed negative CRE from June through August. Values and durations of positive and negative CRE likely vary based on latitude and the time of melt onset, which alters the surface albedo and changes from year to year. Kay et al. (2008) postulate that a lack of summertime cloudiness in the western Arctic contributed to the dramatic ice loss of 2007. Based on previous work, it seems safe to assume that clouds warm the arctic surface by emitting longwave radiation more than they cool the surface by reflecting sunlight, except during summer (June–August).

The interaction of clouds with surface conditions goes both ways: surface changes can also impart changes upon cloud cover. Schweiger et al. (2008) used 40-yr ECMWF Re-Analysis (ERA-40) data as well as Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder Polar Pathfinder (TOVS Path P) data, determining that sea ice retreat during autumn is linked to an increase in cloud height near ice margins because of an increase in surface temperature and a subsequent decrease in static stability. Kay and Gettelman (2009) disagree, finding more low clouds over open water during autumn in the Arctic. Their study focuses on just the 2006–08 period and uses cloud data from CloudSat and Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP). Whether cloud changes are responsible for changes in Arctic sea ice and temperature, or vice versa, apparently has to do with the seasonality of the changes.

Published studies of Arctic cloud trends show little consistency with one another. Wang and Key (2005) used Advanced Very High Resolution Radiometer (AVHRR) satellite data from 1982 to 1999, obtaining trends of −6%, +3%, +2%, and −2% decade−1 during winter, spring, summer, and autumn, respectively, for the entire area north of 60°N. Seasons are defined as follows: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). Schweiger (2004) used satellite data from the TOVS Path P between 1980 and 2001 for all ocean areas north of 60°N, finding seasonal trends of −4%, +5%, +0%, and +0% decade−1 for winter through autumn, respectively. Satellite retrieval of Arctic clouds can be difficult because of a lack of contrast in albedo and temperature between clouds and the surface, and because a limitation in pixel size can miss the finescale detail of cloud cover. Using surface observations from 1971 to 1996, Warren et al. (2007, their Fig. 7) found large positive cloud cover trends over the Arctic land area in winter and spring, and small negative trends in summer and autumn. These three studies disagree in many places, though they do all agree on a positive springtime trend in cloud cover, but they also represent differing regions and time spans (We show below that when the surface data are extended by 11 yr, trends are positive in all seasons). The differences between satellite- and surface-based Arctic cloud trends are under investigation (Eastman and Warren 2010).

General circulation models have been predicting changes in Arctic clouds and precipitation in response to global warming caused by increases in greenhouse gases. Vavrus (2004), using GENESIS2 under 2 × CO2, predicts an increase in low-level cloud cover and an increase in Arctic precipitation after a 20-yr equilibration period. Using the Community Climate System Model, version 3 (CCSM3), Vavrus et al. (2010) also predict an increase in Arctic cloudiness throughout this century, especially in autumn and winter. The increase in the CCSM3 cloud cover is due to increased evaporation from a warmer Arctic Ocean. Also using the CCSM3 and the Special Report on Emissions Scenarios (SRES) A1B emissions scenario, Gorodetskaya and Tremblay (2008) predict an increase in cloud liquid water path (LWP) during the twenty-first century, especially in winter. This increase in LWP brings about increasing positive longwave CRE. Using a model ensemble mean and the SRES A1B emissions scenario, Vavrus et al. (2008) predict a cloudier Arctic during the twenty-first century, especially during autumn and at low and high levels. A decrease is predicted very near the surface (fog), which may be related to the increase in open water reducing static stability, as described by Schweiger et al. (2008). Walsh et al. (2002) also used an ensemble of numerous GCMs and found a consistent model projection for increased precipitation, though these models are shown to substantially over-predict the currently observed precipitation. On the other hand, Warren et al.’s (1999) analysis of drifting-station
measurements found a decrease of May snow depth on multiyear sea ice from 1954 to 1991; the seasonal progression of the trend suggested that its cause was a decrease in wintertime snowfall. A consensus among modeling studies is that an increase in both precipitation and clouds is expected as the Arctic warms, especially low and liquid clouds, excluding fog. These predicted changes suggest that there will be an increase in longwave CRE, furthering the Arctic warming except during summer.

The Arctic Ocean exhibits a dramatic seasonal cycle of cloud cover. Vowinckel (1962), analyzing reports from drifting stations, showed wintertime cloud cover north of 60°N steady at a low value, jumping up to a higher summer value in May and dropping just as abruptly in September–October. The pattern was more pronounced at higher latitudes. His plot was reproduced by Vowinckel and Orvig (1970), and the pattern for 80°–90°N was confirmed in more recent surface observations by Hahn et al. (1995, their Fig. 13a). Wang and Key (2005, their Fig. 2) compared Arctic cloud climatologies from surface observations, TOVS Path P, and AVHRR satellite data for areas north of 80°N. All three agree that there is a summertime maximum in Arctic cloud cover and a minimum in April. Using SHEBA lidar and radar, Intrieri et al. (2002) showed that cloud cover occurred most frequently in September and least frequently during February. The SHEBA data showed that cloud phase varied seasonally, with mainly liquid clouds in summer (95% liquid in July) and mostly ice clouds in winter (25% liquid in December). Walsh et al. (1998) compared numerous precipitation studies and models for areas north of 70°N. The comparison indicated that models grasp the yearly cycle of precipitation well, and that precipitation has a summertime maximum, following the cloud cycle, and decreases toward the pole. The consensus of the observational studies and models is that the Arctic experiences a seasonal cycle in cloud cover and precipitation, with peaks of precipitation, cloud cover, and cloud liquid water content (LWC) during summertime and a minimum in cloud cover and precipitation in winter and early spring.

Arctic climate variations and changes can be tied to changes in circulation, such as the Arctic Oscillation (AO). In its positive phase, the AO is characterized by an increase in midlatitude westerlies and, in the Arctic, decreased sea level pressure and altered large-scale wind patterns. Between about 1989 and the turn of the century, the AO index experienced a prolonged positive phase, but has recently trended to a more neutral state, as shown by Overland and Wang (2005). Rigor et al. (2002) showed that a high wintertime AO reduces ice concentration in the east Siberian and Laptev Seas. This occurs because the Beaufort gyre weakens during high AO years, causing a decline in ice recirculation. According to Rigor et al. (2002), the AO can explain 64% of the variance in the eastern Arctic sea ice concentration. Belchansky et al. (2004) have also concluded that sea ice melt begins earlier and ends later following a winter with a high AO index. An Arctic cloud response to the AO has not been investigated, but could be important in enhancing or reducing the effects of the AO on sea ice concentration and Arctic temperature.

This work will further investigate seasonal cycles and interannual variations of cloud types over Arctic land and ocean areas from 1954 to 2007, and their relations to surface temperature, sea ice extent, and the Arctic Oscillation.

2. Cloud data

Cloud data for this study come exclusively from surface synoptic observations reported from weather stations on land, drifting stations on sea ice, and ships. The observations are reported in the synoptic code of the World Meteorological Organization (WMO 1974). The reports were processed into a database of individual cloud reports known as the Extended Edited Cloud Reports Archive (EECRA; Hahn and Warren 1999). The EECRA data were then averaged over monthly and seasonal time periods to create a surface observation–based cloud climatology (Hahn and Warren 2003, 2007) for each weather station on land, and for grid boxes of 5° resolution over land and 10° resolution over the ocean. Day average, night average, and “day–night average” values are available in the global climatology, with day defined as between 0600 and 1800 LT. Because solar illumination in the Arctic varies more with the seasonal cycle than with the day–night cycle, this study exclusively uses the day–night average cloud amount. The EECRA has subsequently been updated through 2008. Grid boxes are approximately equal area boxes, meaning that longitude bounds increase toward the pole. For this work, a regional climatology has been created for the Arctic, defined as all areas north of 60°N.

Surface observations are generally reported at 3-h intervals 8 times daily, starting at 0000 UTC. Cloud amounts are reported in octas (eighths), with sky cover (N) ranging from 0 to 8. A “sky obscured” value (N = 9) can also be reported. Sky-obscured observations are further processed using the present-weather code to determine the cause of the obscuration (usually fog or precipitation), and assigning a corresponding cloud type if appropriate. Cloud types are reported at three levels: low, middle, and high. Observations of middle- and high-level clouds are fewer in number because upper levels are often obscured by lower clouds. In two-layer situations, a random overlap assumption is made to determine the
amount of upper-level cloud from the reports of N and the low-cloud amount (Nh). When the middle and/or high level cannot be seen because of lower overcast, the average frequency of occurrence and the average amount of cloud cover when a cloud is present (amount when present) are assumed to be the same as when those levels can be seen. This assumption was investigated by Warren et al. (1986, 1988), by comparing the cirrus amounts under three conditions (alone, together with a middle cloud but no low cloud, or together with a low cloud but no middle cloud), and finding little difference among these situations. There are both positive and negative correlations among clouds occurring simultaneously at different levels. These correlations were investigated by Warren et al. (1985), but the correlations vary with geographical location, so they were ignored in the production of the global climatology.

The cloud observations from land stations have been processed for the period of 1971–2007. Original data come from the Fleet Numerical Oceanography Center (FNOC) from 1971 to 1976, the NCEP archive from 1977 to 1996, and the Integrated Surface Database (ISD) archive from 1997 through 2007, available through the National Climatic Data Center [NCDC; Dataset Index Identifier (ISD) 3505]. A total of 638 synoptic stations, selected for having long periods of record, are used in this study (Fig. 1).

Cloud observations from ships and drifting stations have been processed for 1954–2008 and entered into the EECRA [the 2009 update of Hahn and Warren (1999)]. The original data source was the Comprehensive Ocean–Atmosphere Data Set (COADS; Woodruff et al. 1987, 1998; Worley et al. 2005). For our climatology, ocean cloud observations are organized into gridbox average values for long-term means and yearly means for months and seasons. The “10” grid boxes used are approximately equal area, ~1100 km on a side, shown by the dotted lines in Fig. 1. The cloud cover value we report for a box is the mean of all of the observations (land and ocean separated) taken within the box over a specified time period. Figure 2 shows the average number of cloud observations (in hundreds) per year within each grid box.

The archive also contains noncloud variables, such as solar altitude and relative lunar illuminance, which are used to calculate the sky brightness indicator, which dictates whether sufficient light was available to make a reliable cloud observation at night. Hahn et al. (1995) developed a criterion for adequate illuminance; it corresponds to the brightness of a half moon at zenith or a full moon at 6° elevation. This requirement allows the use of ~38% of the observations made with the sun below the horizon.

Weather stations were selected for use in the cloud climatology according to criteria given by Warren et al. (2007). Specifically, stations were selected if they normally report cloud types, have sufficiently long records for trend analysis (20 observations per month in January or July for a minimum of 15 yr), and have an adequate number of day and night observations (at least 15% of the observations must be taken at night).

We develop a climatology of total cloud cover and the amounts of nine cloud types: five low-cloud types...
When studying composite regions within the Arctic Ocean, coastal and island stations are used and treated identically to ship observations. This was done because the number of ship observations is relatively small. This required the weighting of all of the yearly anomalies from coastal and island stations and yearly anomalies from ships and drifting stations within the box by number of observations, then computing the yearly mean anomaly for the box. The regional mean anomaly was then computed by weighting the individual gridbox anomalies by the area of the Arctic Ocean within that box. In this way it was possible to use observations from land as well as ocean to study interannual variations in clouds over the Arctic Ocean.


3. Arctic cloud amounts and the seasonal cycle

Average cloud amounts are determined for total cloud cover and nine cloud types for the grid boxes shown in Fig. 2. For this analysis, boxes are grouped to reduce statistical noise and to observe geographical patterns in cloud cover. We group boxes either by latitude or by the similarity of their cloud climatologies (particularly their seasonal cycles). Long-term mean cloud amounts, from which anomalies are computed below, cover the span of 1971–96 over land and 1954–97 over the ocean. These long-term means are the values that are archived as NDP-026D and NDP-026E in Hahn and Warren (2003, 2007; online at http://www.atmos.washington.edu/CloudMap).

Mean cloud amounts over land and ocean areas in the Arctic are shown for each type and season in Table 1. Ocean areas are cloudier than land at low levels and less cloudy at higher levels. The dominant cloud types are Sc, Ns, Ac, and high clouds. Clear-sky scenes are more common over land than over the ocean.

A strong seasonal cycle is present in Arctic cloud cover, with summer cloudier than winter. Figure 3a shows that the cycle is more pronounced at higher latitudes. This figure closely resembles a figure presented by Vowinckel (1962) and Vowinckel and Orvig (1970), but our values are higher in winter, consistent with the finding of Hahn et al. (1995) of a positive multidecadal trend in wintertime cloud cover from 1954 to 1991. Figure 3b shows that this seasonal cycle is primarily attributable to low stratiform cloud cover, the sum of the three types (St, Sc, and fog). These low types show a dramatic rise from April to May and a slower decline in autumn.

The above-mentioned cycle, when studied more carefully, shows a less direct relationship with latitude and instead becomes more geographically dependent upon landmasses and oceanic regions in the Arctic. For the
The next few figures we divide the Arctic land and ocean regions each into two separate climatic regions, “high Arctic” and “low Arctic,” based on their seasonal cycles of total cloud cover (Fig. 4). The “high Arctic” regions are characterized by the sharp rise in total cloud cover during spring and subsequent sharp decline during autumn. The criterion for defining the high Arctic is a rise of at least 5% in total cloud cover between April and May and a drop of at least 5% between October and November. A high Arctic regime over the ocean is required to have 10% more cloud cover during the cloudy season than in the noncloudy season. Over land, a high Arctic regime only has to have greater cloud cover between April and October than the rest of the year. The distinct high Arctic pattern is not present in the low Arctic, where the seasonal cycle is much weaker. The boundary separating high and low Arctic is different for land than for ocean (Fig. 4).

The seasonal cycle of cloud cover over the high Arctic on both land and ocean (Fig. 5) is shown to be driven by low stratiform cloudiness (St + Sc + fog). Individual cycles for these three types, as well as for Ns, are shown in Fig. 6. Nimbostratus was excluded from the sum in Figs. 3 and 5 because the atmospheric conditions associated with it are different than for the other stratiform types. A midsummer increase in fog compensates for decreases in St and Sc, resulting in a nearly constant value of St + Sc + fog through the summer.

The springtime increase of stratus clouds over the Arctic Ocean was attributed by Herman and Goody (1976) to the northward advection of water vapor from warming waterlogged land areas surrounding the ocean. Using data from aircraft and the ECMWF analysis, Curry and Herman (1985) claimed that the large low-cloud amount observed in June of 1980 over the Beaufort Sea was due to low-level moisture advection and cooling resulting from radiation and boundary layer turbulence. That interpretation was challenged by Beesley and Moritz (1999), who instead attributed the seasonal cycle of low stratiform clouds to the presence of ice crystals in winter clouds and their absence in summer clouds. Their model showed that below a threshold temperature of $-10^\circ$C...
the residence time of cloud particles decreased substantially, reducing the time-averaged cloud cover. Figure 7 shows the seasonal cycles of the remaining cloud types. For middle and high clouds, the amounts shown include our estimates of the amounts hidden above lower clouds, using the random overlap assumption (Hahn and Warren 1999). Because of overlap, the sum of the individual cloud-type amounts exceeds the total cloud cover.

Altocumulus exhibits an increase in summer, which is smaller and less abrupt than that of low stratiform clouds. The seasonal cycle of high (cirriform) clouds is nearly a mirror-image of Ac, and As shows no seasonal cycle, so that the sum of Ac, As, and high clouds is nearly constant through the year. Cumulonimbus exhibits opposing seasonal cycles in the high Arctic and low Arctic regions. The high Arctic Ocean has almost no Cb at any time. The low Arctic land has Cb in summer but not in winter, but the low Arctic Ocean has more Cb in winter. This winter maximum is likely due to the prevalence of cold-air outbreaks over open water in the low Arctic region, triggering open cellular convection or cloud streets. This situation occurs frequently in areas of warm ocean downwind of cold land, particularly in the North Atlantic.

4. Trends of Arctic cloud amounts

Trend analysis is done for individual stations and grid boxes during all seasons in a way similar to that described in Warren et al. (2007). To reduce the effects of outliers on trends, the median-of-pairwise-slopes method (Lanzante 1996) is used to compute trends. A minimum of 50 observations per land station or ocean grid box per season per year is required for a seasonal cloud amount to be included in trend analysis. Over land, there must be a span of at least 20 yr present, and within that span there must be a minimum of 15 yr of data. Over the ocean, since the period of record is longer, a minimum span of 30 yr is required with at least 25 yr of data in each box. A trend is plotted if its magnitude exceeds its uncertainty, or if its uncertainty (the standard deviation of the slope value for the linear fit) is $<2\% \text{ decade}^{-1}$.

FIG. 4. Geographic boundary between the low Arctic and high Arctic over (left) ocean and (right) land areas.

FIG. 5. The seasonal cycles of total cloud cover and stratiform cloud cover in the high and low Arctic over (a) land and (b) ocean.
Figure 8 illustrates some geographic patterns of cloud trends over the Arctic. Trends displayed in both frames (units of 0.1% decade$^{-1}$) represent combined land and ocean data spanning 1971–2007. The trends are not uniform over the entire Arctic, but they do aggregate into large regions of similar signs. These trends generally show little relationship with the boundaries of the high and low Arctic. Figure 8a shows a large increase in summer St over the central Arctic and a weak decrease at lower latitudes. Figure 8b shows a different pattern in the distribution of annual average trends of precipitating clouds. Positive trends are found over central Siberia and over the Canadian Arctic. A negative trend is apparent over much of northern Europe and coastal Asia as well as over Alaska and the entire Arctic Ocean. This negative trend of precipitating cloud (mostly Ns) is consistent with the negative trend of snow accumulation found by Warren et al. (1999). The Arctic mean trend shown at the bottom of each figure is the area-weighted mean of individual anomaly time series over the Arctic land and ocean regions, which may differ from the mean of all numbers on the map. These two maps for St and Ns were chosen for display because these cloud types are prominent in the discussion. A complete set of maps for all cloud types during all seasons, for land, ocean, and total area (a total of 144 maps) is available online (see http://www.atmos.washington.edu/CloudMap).

Table 2 shows the average trend values for the Arctic land, ocean, and combined land and ocean. These area-averaged trends are not particularly large, with magnitudes rarely exceeding 1% decade$^{-1}$. Trends are plotted in bold if their magnitude exceeds their standard deviation. The trends are shown for total cloud cover, for seven individual types, and for the combined middle (As, Ac, and Ns), low (St, Sc, fog, Cu, and Cb), precipitating (Cb and Ns), and nonprecipitating middle (As + Ac) types. Altostratus (As) and Ac are combined because their individual trends are often opposing, which could be the result of a subtle change over time in the observing procedure in how middle clouds are distinguished. Arctic land trends (Table 2a) show an increase in overall cloud cover, but numerous trade-offs in types. Stratocumulus clouds are increasing, but the other
low stratiform clouds (St and fog) are decreasing. Nimbostratus is decreasing, but this decrease is being countered by a strong increase in Cb. These trade-offs indicate an increase of convective activity. The two precipitating types combine to make an overall positive trend over land. Midlevel clouds as a whole are increasing, driven by an increase in nonprecipitating middle cloud cover.

Table 2b shows trends over the ocean for the period of 1954–2008. The trends in total cloud cover are weak and are not significant in any season, but individual types show interesting results. Oceanic low stratiform cloud cover is changing in the opposite manner to that over land. Stratus and fog are increasing while Sc is decreasing. Cumulonimbus is also behaving differently over the ocean, with significant decreases shown for all seasons. Nimbostratus is trending negatively during spring and summer, and only increasing during the winter. The combination of both precipitating cloud types produces a decreasing trend. Middle clouds are decreasing, again in opposition to trends over land. Ocean trends have also been computed for the same time span as those over land. Over the shorter span, summer and autumn total cloud cover do show significant increases, and the decrease in Sc and increase in fog are less significant, but otherwise little change is seen in types when comparing trends for the different spans.

In Table 2c, the trends (1971–2007) in cloud cover over the entire Arctic are shown. These are computed by area weighting the land and ocean anomalies to form an average anomaly, and fitting a trend line to the average anomaly time series. The overall trends show a slight positive trend in total cloud cover in all seasons. The increase appears to be driven primarily by increasing low cloud cover, and is partially countered by a decrease in precipitating cloud amount. These changes are likely a complex feedback associated with the large-scale changes observed in Arctic climate. The impact of these cloud changes is likely to increase downward longwave radiation, leading to a net warming in winter, spring, and autumn. The observed decrease in precipitating cloud cover, and the likely accompanying decrease in snowfall, may be acting to enhance ice melt in summer by decreasing the surface albedo.

5. Clouds and Arctic sea ice

To study the relationships between cloud cover and sea ice, composite time series have been analyzed using a variety of methods for two regions: (i) the Arctic Ocean as a whole and (ii) the region of large recent sea ice anomalies, extending from the Laptev Sea, through the east Siberian and Chukchi Seas, to the Beaufort Sea. This latter region we call “Beaufort–Laptev’’ (“B–L’’), for brevity’s sake. The B–L region is similar to the region studied by Schweiger et al. (2008); it represents the region where the sea ice margin, as observed by the NSIDC, shows the most interannual variability, which should ideally show a strong cloud precursor or response to changes in ice extent. These regions are shown on the map in Fig. 9; they include all land-based synoptic stations bordering the Arctic Ocean between 80°E and 120°W, but exclude stations along the Chukchi Sea south of 70°N.
A trend analysis of all cloud types has been done for these regions. We will show figures for the most noteworthy results; otherwise, the results are shown in the tables. We correlate the interannual variations of cloud types with SAT, total sea ice extent, and the Arctic Oscillation index, as defined by Thompson and Wallace (1998). A superposed epoch study is done using the difference between cloud amounts for each type during the 5 yr with least and the 5 yr with greatest sea ice extent.

**a. Trends**

Selected time series of cloud cover anomalies are shown in Fig. 10 for the Arctic Ocean and B–L regions. Trend lines are computed; a trend is considered significant if its magnitude exceeds its uncertainty (i.e., the standard deviation of the slope of the linear fit).

Significant positive trends of total cloud cover are found in three seasons over the B–L, and two over the Arctic Ocean (Fig. 10a). Only wintertime lacks a significant trend in either region, though both regions do exhibit an increase. In springtime, the largest trend in total cloud cover is observed over the B–L, while in autumn the trend is greatest over the entire Arctic Ocean. Spring and autumn display the largest increase in both regions with more modest increases during summer and winter.

Trends in individual cloud types tend to keep their sign throughout the year rather than show different tendencies between seasons. Figure 10b shows low clouds increasing year-round, and this increase is being countered by a consistent, strong decrease in precipitating clouds (mostly Ns, but also Cb; Fig. 10c) and fog. Precipitating clouds show higher values in some seasons of the past 2–3 yr, but the duration of this recent recovery is too short to make any conclusions about a possible trend reversal. The positive trend of low-cloud amount, which appears to be the primary driver for the trend of total cloud cover, is mainly the result of increases in low stratiform clouds. The type of low stratiform cloud that is changing differs between regions,

### Table 2. Trends in Arctic cloud amounts (% decade $^{-1}$), from linear fits to seasonal averages. Values are plotted in bold if their trend exceeds their standard deviation.

<table>
<thead>
<tr>
<th>Region</th>
<th>Total</th>
<th>St</th>
<th>Sc</th>
<th>Fog</th>
<th>Cu</th>
<th>Cb</th>
<th>Ns</th>
<th>As + Ac</th>
<th>High</th>
<th>Middle</th>
<th>Low</th>
<th>Precipitating</th>
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<tr>
<td><strong>Arctic land trends (1971–2007)</strong></td>
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<td></td>
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<tr>
<td>DJF</td>
<td>0.5</td>
<td>−0.5</td>
<td>1.3</td>
<td>−0.1</td>
<td>0.1</td>
<td>0.3</td>
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<td>0.2</td>
<td>1.2</td>
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<tr>
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<td>1.1</td>
<td>−0.1</td>
<td>0.0</td>
<td>0.5</td>
<td>−0.3</td>
<td>0.7</td>
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<td>0.5</td>
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<td>0.4</td>
<td>−0.2</td>
<td>−0.1</td>
<td>0.6</td>
<td>−0.4</td>
<td>0.6</td>
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<td>0.2</td>
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<tr>
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<td>−0.8</td>
<td>0.9</td>
<td>−0.1</td>
<td>0.1</td>
<td>0.7</td>
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<td>DJF</td>
<td>0.1</td>
<td>1.5</td>
<td>−0.7</td>
<td>0.1</td>
<td>0.2</td>
<td>−1.1</td>
<td>0.4</td>
<td>−1.0</td>
<td>0.0</td>
<td>−0.5</td>
<td>0.2</td>
<td>−0.7</td>
</tr>
<tr>
<td>MAM</td>
<td>−0.3</td>
<td>1.1</td>
<td>−0.4</td>
<td>0.3</td>
<td>0.6</td>
<td>−1.1</td>
<td>−0.4</td>
<td>−0.7</td>
<td>−0.4</td>
<td>−1.1</td>
<td>0.3</td>
<td>−1.6</td>
</tr>
<tr>
<td>JJA</td>
<td>−0.1</td>
<td>1.3</td>
<td>−0.7</td>
<td>0.2</td>
<td>0.4</td>
<td>−0.3</td>
<td>−0.5</td>
<td>−0.2</td>
<td>0.3</td>
<td>−0.4</td>
<td>0.9</td>
<td>−0.8</td>
</tr>
<tr>
<td>SON</td>
<td>0.0</td>
<td>1.2</td>
<td>−0.2</td>
<td>0.0</td>
<td>0.5</td>
<td>−0.6</td>
<td>−0.1</td>
<td>−0.2</td>
<td>0.0</td>
<td>−0.8</td>
<td>0.9</td>
<td>−0.7</td>
</tr>
<tr>
<td><strong>Arctic trends (1971–2007)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DJF</td>
<td>0.3</td>
<td>0.2</td>
<td>0.8</td>
<td>0.0</td>
<td>0.1</td>
<td>−0.5</td>
<td>0.2</td>
<td>−0.6</td>
<td>0.2</td>
<td>0.0</td>
<td>0.8</td>
<td>−0.4</td>
</tr>
<tr>
<td>MAM</td>
<td>0.2</td>
<td>0.5</td>
<td>0.3</td>
<td>0.0</td>
<td>0.2</td>
<td>−0.4</td>
<td>−0.4</td>
<td>0.0</td>
<td>−0.5</td>
<td>−0.4</td>
<td>0.7</td>
<td>−0.9</td>
</tr>
<tr>
<td>JJA</td>
<td>0.2</td>
<td>0.2</td>
<td>−0.3</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>−0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.0</td>
<td>0.7</td>
<td>−0.4</td>
</tr>
<tr>
<td>SON</td>
<td>0.5</td>
<td>0.8</td>
<td>0.5</td>
<td>−0.1</td>
<td>0.3</td>
<td>−0.2</td>
<td>−0.2</td>
<td>0.6</td>
<td>−0.2</td>
<td>0.0</td>
<td>1.4</td>
<td>−0.5</td>
</tr>
</tbody>
</table>

---

**FIG. 9.** Subregions within the Arctic defined for comparisons of clouds with other variables.
with St mainly increasing over the Arctic Ocean (Fig. 10d), but Sc increasing over the B–L.

b. Correlations

Cloud cover anomalies are correlated with September sea ice extent anomalies, seasonal temperature anomalies, and the Arctic Oscillation index. Correlations were also done with detrended time series in order to assess the reliability of our results. Tables are shown only for the unaltered time series, because most relationships remained intact regardless of detrending. Correlations that are significant at the 95% level are printed in bold in Tables 3–5.

Correlation coefficients between September sea ice extent (NSIDC 2008) and total cloud cover during all

![Fig. 10. Time series of (a) total cloud cover anomalies, (b) low-cloud anomalies, and (c) precipitating cloud anomalies (1971–2007) over the (left) Arctic Ocean and (right) Beaufort–Laptev region. (d) Time series of stratus cloud anomalies (1971–2007) over the (left) Arctic Ocean and (right) stratocumulus cloud anomalies over the Beaufort–Laptev region.](image-url)
seasons of the same year are displayed in the leftmost column of Table 3. A significant negative correlation between cloud cover and ice extent is present during spring and autumn, indicating that low autumn ice extent is associated with increased cloudiness over the ice. In both winter and summer there are weaker, but still negative, correlations. During summer, we expected the sign of the correlation to change to positive because of the dominance of shortwave CRE, and these values alone change sign when the time series are detrended. We have to conclude that summertime total cloud cover is uncorrelated with September sea ice extent, but there may be significant correlations with individual cloud types. Low clouds appear to be the major contributor to the pattern of correlations shown for total cloud cover, specifically St and Cb, which correlate negatively throughout the year with September ice extent. September sea ice extent correlates positively with summertime Sc and Ns. The relationship between precipitation and ice extent is strongest during summer, though over the B–L it is present from winter through summer.

Table 3. Correlation coefficient of seasonal average cloud amount with September Arctic sea ice extent in the same year for years 1971–2007. Values are shown in bold if 95% significant.

<table>
<thead>
<tr>
<th></th>
<th>Arctic Ocean Region</th>
<th>Beaufort–Laptev region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>St</td>
</tr>
<tr>
<td>DJF</td>
<td>0.2</td>
<td>-0.4</td>
</tr>
<tr>
<td>MAM</td>
<td>-0.4</td>
<td>-0.3</td>
</tr>
<tr>
<td>JJA</td>
<td>-0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>SON</td>
<td>-0.5</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

Table 4 shows correlations of cloud amounts with seasonal SAT anomalies as determined by the NCEP–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996). Positive correlations are found in winter, spring, and autumn. In summer the correlation is negative but insignificant. A likely reason for the weak correlation during summer is the lack of variability in summertime SAT over melting ice. When correlations are made using reanalysis temperatures at 850 and 500 mb, the summertime positive correlation becomes significant.

Low clouds, specifically St, drive the positive correlation during winter, spring, and autumn, though nonprecipitating middle clouds also contribute. SAT correlates negatively with nonprecipitating middle clouds, Sc, and precipitating clouds during summer. For the remainder of the year, precipitating clouds show little relationship with temperature.

Total cloud cover is also correlated with the seasonal Arctic Oscillation (Table 5). In spring and summer, the AO and total cloud cover correlate positively, and the

Table 4. Correlation coefficient of seasonal average cloud amount with seasonal average surface air temperature. Values are shown in bold if 95% significant.

<table>
<thead>
<tr>
<th></th>
<th>Arctic Ocean region</th>
<th>Beaufort–Laptev region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>St</td>
</tr>
<tr>
<td>DJF</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>MAM</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>JJA</td>
<td>-0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>SON</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

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correlations are significant over the entire Arctic Ocean. In autumn, the correlation is negative and significant over the B–L, but not over the Arctic Ocean as a whole. The wintertime correlation is not substantial for either region. Interestingly, trends in the AO are positive in all seasons except autumn, and, though small, these trends suggest that changes in circulation resulting from the AO could be associated with the increase in cloud cover throughout much of the year. Variations in cloud types do not correlate as strongly with the AO as with other variables. The AO appears to have a stronger relationship with middle and high clouds, with positive correlation during spring and summer, and with precipitating clouds, which correlate positively during summer. A negative correlation of the AO with fog is also present in summer, autumn, and winter.

c. Superposed epochs

Two subsets of cloud anomaly data are chosen based on September sea ice extent between 1979 and 2007 (consistent data on sea ice extent are available beginning in 1979). In this case, yearly values of September sea ice extent are ranked from greatest to least, and cloud cover anomalies during the 5 yr with the greatest September sea ice extent are compared to the 5 yr with the least ice extent. Anomalies are averaged for each of the 5-yr subsets, and the mean anomaly for the high-ice years is subtracted from the mean anomaly for the low-ice years, producing a difference of mean cloud cover (DMCC). A Student’s t test is done to determine whether the DMCC is significant at the 90% level. A positive DMCC indicates that cloud cover is higher during years with lower September sea ice extent. Because of the declining trend of Arctic sea ice, the low-ice years are all post-2000 and the high-ice years are all pre-2000 (Fig. 11a).

This analysis has been done over the B–L and over the entire Arctic Ocean region for all cloud types and during all seasons in the year of the ice extent anomaly, plus the preceding winter (Table 6). All DMCC values for total cloud cover during all of the seasons analyzed are positive, with statistically significant values during autumn.

<table>
<thead>
<tr>
<th>Table 5. Correlation coefficient of seasonal average cloud amount with seasonal average Arctic Oscillation index. Values are shown in bold if 95% significant.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic Ocean region</td>
</tr>
<tr>
<td>Total St Sc Fog Cu Cb Ns As + Ac High Middle Low Precipitating</td>
</tr>
<tr>
<td><strong>DJF</strong></td>
</tr>
<tr>
<td><strong>MAM</strong></td>
</tr>
<tr>
<td><strong>JJA</strong></td>
</tr>
<tr>
<td><strong>SON</strong></td>
</tr>
</tbody>
</table>

Beaufort–Laptev region

<table>
<thead>
<tr>
<th>Total St Sc Fog Cu Cb Ns As + Ac High Middle Low Precipitating</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DJF</strong></td>
</tr>
<tr>
<td><strong>MAM</strong></td>
</tr>
<tr>
<td><strong>JJA</strong></td>
</tr>
<tr>
<td><strong>SON</strong></td>
</tr>
</tbody>
</table>

FIG. 11. (top) Time series of September Arctic sea ice extent anomaly with high- and low-ice years shown, and (bottom) the accompanying time series of autumn low cloud cover anomaly showing cloud anomalies during high- and low-ice years.
for both regions. Analyzing cloud types shows that low clouds, particularly St, are the cause of the greater autumn cloud cover during a low-ice year, with low-cloud amounts greater by over 10%. Figure 11b shows the autumn time series of low cloud cover over the B–L, with high- and low-ice years indicated. Though weaker, the overall pattern of more summer precipitating clouds during high-ice years has stayed intact.

This analysis shows that the total cloudiness during autumn of a low-ice year is significantly greater than that of a high-ice year. All five of the low-ice years had greater SON cloud cover than any of the high-ice years. While many other factors are likely present, this does imply a response of increased cloud cover to increased open water over the Arctic. Summer precipitation also appears to produce a slight positive response in September sea ice extent. A cloud response to changing sea ice is observed because low cloudiness tends to increase substantially during autumn following a particularly low September ice extent. Kato et al. (2006) suggested that an apparent increase of cloud cover in response to reduced Arctic sea ice could diminish the ice–albedo feedback. However, their analysis considered only shortwave radiation. Our study has shown that cloud cover in the Arctic during autumn is typically associated with surface warmth, so it is likely that long-wave effects dominate.

Observed trends in cloud cover appear to act to enhance the effects of Arctic warming in both the Beaufort–Laptev and the Arctic Ocean. This result is consistent with changes observed in sea ice if climate models are correct in predicting that increasing clouds during SON, DJF, and MAM will decrease the ice thickness. Increasing low stratiform cloud cover during spring and autumn is associated with increasing temperature. A difference exists in the type of stratiform cloud increasing in the B–L versus the Arctic Ocean, with St increasing over the B–L and Sc increasing over the Arctic Ocean. This may be linked to the destabilization of the boundary layer caused by the increased area of open water suggested by Schweiger et al. (2008). However, our conclusion of increased autumn low cloud cover may be inconsistent with their findings of an increase in cloud height. The reporting of base height is not reliable in observations over the Arctic, so we cannot be certain that clouds are not moving up, though an increase in middle cloud cover is not seen with a reduction in sea ice in this study. Our finding of increased autumn low cloud cover does agree well with Kay and Gettelman (2009), who attributed the increase to low near-surface static stability, stronger air–sea temperature gradients, and turbulent vertical transfer of moisture.

d. Discussion

This study indicates that increases in Arctic Ocean cloud cover are associated with decreased sea ice extent and warmer temperatures. These relationships are true over the B–L region where maximum variability in ice exists, but they remain significant over the entire Arctic Ocean. Correlations with temperature and sea ice extent are strongest during spring and autumn when the cloud longwave effect dominates. It is shown that low clouds have a strong positive relationship with temperature during these seasons. Precipitating clouds appear to be associated with cooling during summer and subsequently with increased September sea ice extent. A cloud response to changing sea ice is observed because low cloudiness tends to increase substantially during autumn following a particularly low September ice extent. Kato et al. (2006) suggested that an apparent increase of cloud cover in response to reduced Arctic sea ice could diminish the ice–albedo feedback. However, their analysis considered only shortwave radiation. Our study has shown that cloud cover in the Arctic during autumn is typically associated with surface warmth, so it is likely that long-wave effects dominate.

Observed trends in cloud cover appear to act to enhance the effects of Arctic warming in both the Beaufort–Laptev and the Arctic Ocean. This result is consistent with changes observed in sea ice if climate models are correct in predicting that increasing clouds during SON, DJF, and MAM will decrease the ice thickness. Increasing low stratiform cloud cover during spring and autumn is associated with increasing temperature. A difference exists in the type of stratiform cloud increasing in the B–L versus the Arctic Ocean, with Sc increasing over the B–L and St increasing over the Arctic Ocean. This may be linked to the destabilization of the boundary layer caused by the increased area of open water suggested by Schweiger et al. (2008). However, our conclusion of increased autumn low cloud cover may be inconsistent with their findings of an increase in cloud height. The reporting of base height is not reliable in observations over the Arctic, so we cannot be certain that clouds are not moving up, though an increase in middle cloud cover is not seen with a reduction in sea ice in this study. Our finding of increased autumn low cloud cover does agree well with Kay and Gettelman (2009), who attributed the increase to low near-surface static stability, stronger air–sea temperature gradients, and turbulent vertical transfer of moisture.

### Table 6. Difference of mean seasonal cloud amount: low-ice years minus high-ice years. Values are shown in bold if 90% significant.

<table>
<thead>
<tr>
<th>Season</th>
<th>Total St</th>
<th>Total Sc</th>
<th>Total Fog</th>
<th>Total Cu</th>
<th>Total Cb</th>
<th>Total Ns</th>
<th>Total As + Ac</th>
<th>Total High</th>
<th>Total Middle</th>
<th>Total Low</th>
<th>Total Precipitating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beaufort–Laptev region</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DJF (previous)</td>
<td>3.1</td>
<td>2.2</td>
<td>3.2</td>
<td>-0.1</td>
<td>-0.1</td>
<td>0.5</td>
<td>2.2</td>
<td>-0.9</td>
<td>-3.5</td>
<td>1.6</td>
<td>5.7</td>
</tr>
<tr>
<td>MAM</td>
<td>4.0</td>
<td>1.3</td>
<td>0.0</td>
<td>-0.3</td>
<td>-0.5</td>
<td>0.5</td>
<td>-2.0</td>
<td>-0.7</td>
<td>-2.6</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>JJA</td>
<td>1.5</td>
<td>5.7</td>
<td>-3.2</td>
<td>2.1</td>
<td>0.4</td>
<td>0.5</td>
<td>-2.0</td>
<td>-4.5</td>
<td>2.3</td>
<td>-6.8</td>
<td>5.3</td>
</tr>
<tr>
<td>SON</td>
<td>5.6</td>
<td>6.5</td>
<td>2.0</td>
<td>0.8</td>
<td>0.7</td>
<td>2.0</td>
<td>-0.7</td>
<td>2.1</td>
<td>-0.7</td>
<td>-1.6</td>
<td>12.0</td>
</tr>
<tr>
<td>DJF (following)</td>
<td>2.5</td>
<td>3.8</td>
<td>3.3</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.6</td>
<td>-0.4</td>
<td>-1.7</td>
<td>-2.0</td>
<td>-1.5</td>
<td>7.6</td>
</tr>
</tbody>
</table>

| Arctic Ocean region | | | | | | | | | | | |
| DJF (previous) | 1.5 | 2.5 | 2.0 | -0.2 | 0.0 | 0.9 | -0.7 | 0.3 | -0.6 | -0.4 | 5.1 | 0.2 |
| MAM | 6.9 | 1.0 | 2.5 | -0.2 | -0.1 | 1.5 | -2.7 | -0.7 | 4.0 | -3.4 | 4.8 | -1.1 |
| JJA | 0.2 | 4.1 | -3.4 | 0.9 | 0.8 | 1.2 | -2.1 | -5.7 | 3.5 | -7.9 | 3.6 | -1.0 |
| SON | 6.0 | 5.7 | 3.3 | 0.6 | 1.2 | 3.4 | 0.3 | 0.6 | 0.6 | -2.8 | 14.2 | 3.6 |
| DJF (following) | 2.5 | 4.4 | 3.9 | -0.3 | -0.1 | 1.2 | -1.5 | -1.7 | 1.5 | -3.2 | 9.1 | -0.3 |
from the nonice-covered ocean. The decrease seen in fog also substantiates their claim of reduced static stability. The observed decrease in precipitating clouds likely reduces snow cover, reducing surface albedo throughout the summer. Alternatively, because precipitating clouds are generally thick and have a high albedo, the decrease in precipitating clouds during summer may allow for more shortwave radiation to reach the surface, which can cause warming and ice melt regardless of the type of precipitation that is decreasing.

Increasing stratiform cloud cover, and the accompanying decrease in precipitating clouds, suggests a possible link with aerosols. An increase of aerosols would decrease cloud-droplet size and increase droplet number density, as was observed by Garrett and Zhao (2006). This would act to prolong the life of a cloud and reduce precipitation. However, the trend of Arctic aerosols has gone in the opposite direction, as Quinn et al. (2007) have observed with the decreasing sulfate aerosols since the mid-1990s at surface stations in the Arctic.

The relationships observed between the Arctic Oscillation and cloud cover could be the result of changing high-latitude circulation associated with the AO. Changing the phase of the AO could alter the moisture flux into the Arctic during spring and autumn, when moisture at the surface is limited. Vertical motions and inversion strength associated with the altered surface pressure may have an effect on cloud cover and type. It is also possible that changes in the distribution of sea ice and open water caused by anomalous surface winds associated with the AO could feed back on cloud cover. While no definitive explanation is offered by this study, these proposed mechanisms could partially explain some results. More high-level moisture advection over the Arctic Ocean during a positive AO could result in more middle- and high-level cloud. An earlier melt season associated with a positive AO, suggested by Belchansky et al. (2004), may provide a moisture source for more cloud cover during spring. Finally, changing vertical motions and inversion strength may be related to the observed correlation between fog and the AO.

6. Conclusions

The Arctic is a very cloudy region with an annual average of ~70% cloud cover. Clouds are more prevalent over oceanic regions. A distinct yearly cycle of cloud cover exists over higher latitudes within the Arctic. The region exhibiting this cycle is called the “high Arctic,” and cloud cover displaying the high Arctic cycle is bimodal, with cloud cover high in summer and low in winter. Low stratiform clouds are responsible for this cycle, which has been attributed to the cloud response to the annual cycle in air temperature. This pattern is not entirely latitude dependent, but instead appears to be geographically based upon the location of sea ice and the colder continental regions within the Arctic.

Significant trends are present in Arctic cloudiness over the ocean and land. The trends are not uniform over the Arctic, but large regions displaying similar trends are common. Arctic clouds are changing differently over the land and ocean, but overall the trend from 1971 through 2007 shows a slight increase in total cloud cover during all seasons. Low clouds appear most responsible for this trend, and are partially offset by decreases in the amount of precipitating cloud. However, Arctic land areas are seeing an upward trend in precipitating clouds, caused by increasing cumulus-nimbus clouds. The overall decrease in precipitating clouds is taking place mostly over the Arctic Ocean and has not been forecast or simulated in existing modeling studies. Combined, these cloud changes are likely to enhance warming in the Arctic during much of the year.

Clouds over sea ice show an association with warming temperatures and decreasing sea ice, except during summer. As observed over the entire Arctic, there is a substantial decreasing trend in precipitating clouds, but an even larger increase in low stratiform cloud cover. During autumn, a strong, positive low-cloud response to reduced sea ice is seen. Overall, relationships between ice, temperature, and clouds indicate that cloud changes in recent decades may enhance the warming of the Arctic and may be acting to accelerate the decline of Arctic sea ice.

Acknowledgments. An advance version of the ocean cloud update was provided by Carole Hahn. We thank J. Michael Wallace, Cecilia Bitz, Robert Wood, and Axel Schweiger for helpful discussion. John Walsh and two anonymous reviewers provided useful comments. The research was supported by NSF’s Climate Dynamics Program and NOAA’s Climate Change Data and Detection (CCDD) program, under NSF Grants ATM-06-30 428 and ATM-06-30 396.

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